The emergence of climate change mitigation action by society – An agent-based scenario discovery study

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ABSTRACT

Studying society's response to climate change is hampered by two main factors. First, the dynamics of society's response to climate change are emergent and complex, as mitigation action arises out of the actions and interactions of the many actors in society. Second, society's response to climate change is subject to many uncertainties. The emergence of climate change mitigation action by society has been represented in an agent-based model. The model represents a two-level game involving governments and citizens changing their emission behaviour in the face of climate change through mitigation action. The consequences of uncertainties pertaining to the system have been explored by applying exploratory modelling and analysis. Insights gained from this exploration have been used to construct two internally consistent and plausible narratives on the pathways of the emergence of mitigation action. The first narrative highlights how and when strong mitigation action emerges. The second narrative highlights how and when weak mitigation action emerges. These narratives help in conveying the consequences of the various uncertainties influencing the emergence of climate change mitigation action by society.

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1. Introduction

In the fall of 2015, France will be hosting the 21st Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change. The ambition is to achieve a new international agreement on climate change response, aiming to limit global warming to 2C° (COP21, 2015). Reaching international agreements on climate change is proving to be a very difficult (Weiler, 2012). The difficulty stems from the collective nature of the problem, with common but differentiated ethical responsibilities, in combination with the many uncertainties inherent to it (Ostrom, 2012). In contrast to the extensive research on the climate system the impact of anthropogenic activities on the it, the way in which mankind will respond to climate change has received substantially less attention in modelling and scenario studies (Giupponi, Borsuk, de Vries, & Hasselmann, 2013). In this research we focus on exploring how climate change mitigation action by society can emerge.

Studying society's response to climate change is hampered by two main factors. First, the dynamics of mitigation action by society are emergent and complex and should be consider that way. The system in which climate change mitigation action by society emerges is governed and influenced by a complex network of many social systems, comprising of producers, generators, suppliers, end users, environmental and economic regulators, policy makers, et cetera (Chappin, 2011). These actors learn from their behaviour and from the behaviour of others, resulting in behavioural change. Simultaneously, the behaviour of the various actors is subject to bounded rationality. The overarching dynamics of society's response to climate change are therefore emergent and co-evolving. This self-organising emergent system behaviour cannot be predicted by understanding the individual actors in isolation. Gaining insight in this complex system therefore requires dealing with issues such as the heterogeneity of actors and the bounded rationality in their behaviour; influential factors within the energy transition (Bale, Varga, & Foxon, 2015; Giupponi et al., 2013). Agent-based modelling (ABM) is a modelling technique that can be used to model the actions of and interactions between agents under influence of their state and the state of the environment. ABM allows simulating autonomous and heterogeneous agents with bounded rationality and adaptive agent behaviour over local interactions. In this way, the emergence of macroscopic regularities can be discovered from a bottom-up perspective (Epstein, 2007). ABM thus appears to be a suitable modelling technique to capture the emergence of climate change mitigation by society. The ABM model constructed for the purpose of this research will be further described in section 2 of this paper.

The second reason that makes it hard to get insight into the emergence of climate change mitigation by society is that it is subject to many uncertainties. Although there is scientific consensus about the fact that human activities influence climate change, there is uncertainty about the exact extent of this

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influence and about the severity of the future impacts of climate change (Tompkins & Neil Adger, 2005; van Vuuren et al., 2011). Uncertainty also exists with respect to the exact mechanisms that underlie society's response to climate change, such as the time preference citizens apply in order to value future costs and benefits of climate change response (Tol et al., 2013). These uncertainties result in a widespread lack of consensus, both within the scientific community and among policy makers, on the essential facts and mechanisms governing the evolution of society's response to climate change. This effect is amplified by the long time horizon over which the uncertainties manifest (Giupponi et al., 2013; Moss et al., 2010; Weaver et al., 2013).

Currently, society's response to climate change has not been incorporated adequately in modelling studies on climate change and associated impact (Balbi & Giupponi, 2009; Brede & De Vries, 2013). Furthermore, the consequences of uncertainties influencing society's response to climate change should be explored (Gerst, Wang, & Borsuk, 2013). In this research, those elements are combined in order to get a better insight into the emergence of mitigation action by society in the face of climate change and the consequences of uncertainties influencing this emergence. Typically, in studies concerning climate change, uncertainty is addressed through scenario analysis (Gerst, Wang, & Borsuk, 2013). The main rationale for using scenarios is that the time span of interest regarding the consequences of climate change is very long, and the possible consequences of uncertainties are amplified due to to the complex and chaotic dynamics of the system in which climate change takes place (van Vuuren et al., 2012). Scenarios provide an intuitively appealing means to characterise and communicate information about uncertain future states of a system (Bryant & Lempert, 2010; Gerst, Wang, & Borsuk, 2013). We address the following research question in this paper:

What internally consistent and plausible narratives on the emergence of climate change mitigation by society can be identified?

We use a model-based scenario discovery study to identify internally consistent and plausible narratives. We have designed a new modelling process supporting the scenario discovery approach using a combination of agent-based modelling (ABM) and exploratory modelling and analysis (EMA) and apply this modelling process to the emergence of climate change mitigation by society. This paper will present the most important findings of this modelling study.

In Section 2, a description of the ABM on the emergence of climate change mitigation action by society is presented. Section 3 will then provide a detailed elaboration on the scenario discovery approach used to construct narratives on the emergence of climate change mitigation action by. In Section 4 the analysis of the dynamics of the model across the various uncertainties is presented. The paper will result in conclusions, a discussion and recommendations for further research in section 5.

2. Model description

In this research an ABM has been constructed aiming to represent the emergence of mitigation action by society in the face of climate change. The model represents society as a two-level game involving governments and citizens changing their emission behaviour in the face of climate change through mitigation action. Governments and citizens are heterogeneous in their time horizon of assessing future expected climate change impact, resulting in differences in climate change awareness. The climate change awareness of governments and citizens determines the amount of mitigation action they take, resulting in greenhouse gasses (GHG) emission reductions. Citizens influence the mitigation policy of their governments through voting, whereas governments can enforce mitigation action upon themselves and their citizens as a result of international negotiations on climate change response. The two-level game is based on the two-level game theory by Putnam (1988). The international negotiations on climate change response are modelled after the N-player bargaining game in an agent-based model of climate change negotiations by Smead, Sandler, Forber, and Basl (2014). A short elaboration on the internal mechanisms in the model is provided in section 2.1. For a more detailed description of the model, we refer to the formal model description by Greeven (2015a) following the ODD-protocol standards (Grimm et al., 2010). Section 2.2 describes the uncertainties influencing the emergence of climate change mitigation action by society, and how the uncertainties have been incorporated in the model, allowing for exploration of their consequences.

2.1 Short description of the main internal mechanisms in the ABM

Governments and citizens are heterogeneous with respect to the way in which they assess future climate change impact. Governments and citizens predict future cumulative GHG emissions given their individual time horizon and assess the associated climate change impact as depicted in the left figure in Figure 1. Next, the predicted future climate change impacts are translated into climate change awareness. Based on their level of climate change awareness, governments and citizens decide on whether and by how much they are going to reduce their GHG emission level. The heterogeneous time horizon among governments and citizens results in differences in climate change awareness, and thus differences in the emission reduction behaviour of governments and citizens.

We conceptualise the interactions between governments and citizens as a two-level game (Putnam, 1988). Citizens are able to express their political views on how their governments should respond to climate change through voting, thereby influencing the mitigation policy of their governments. Governments base their mitigation policy on their own climate change awareness and the interests of their citizens. They participate in international negotiations on climate change response and as a possible result of these negotiations they are able to enforce mitigation actions on their own mitigation policy and on their citizens.

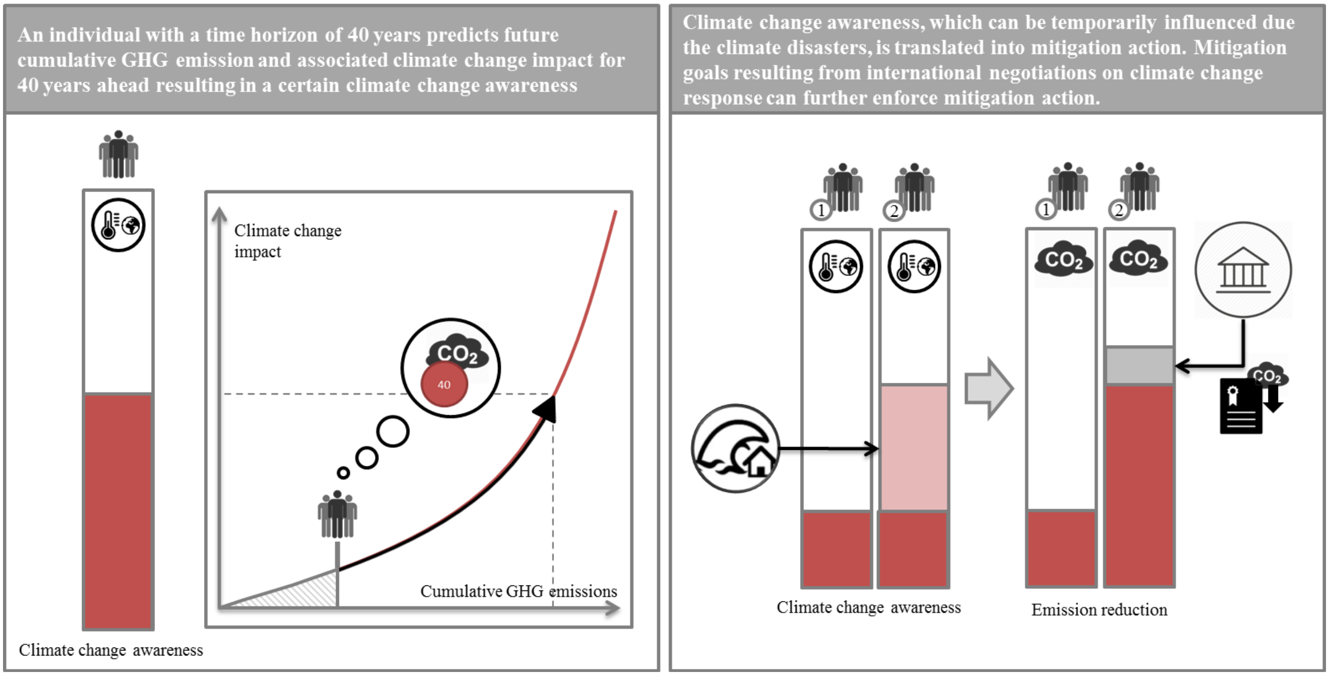


Figure 1: Governments and individuals assess future climate change impact relative to their time horizon resulting in a certain degree of climate change awareness. The climate change awareness of governments and individuals determines the amount of mitigation action they take. This can be influenced by the occurrence of climate disasters and the enforcement of mitigation action as a result of international negotiations on climate change response.

International negotiations on climate change response are performed periodically, aiming for an international agreement on climate change mitigation action. International negotiations are modelled based on the bargaining game of Smead et al. (2014), together with additional ideas from the other climate change negotiation games (Courtois & Tazdaït, 2007; Forgó, Fülöp, & Prill, 2005; Pinto & Harrison, 2003). Smead et al. (2014) propose a modified version of the Nash bargaining game with N-players representing the negotiating countries or coalitions. The bargaining game incorporates learning dynamics, by representing adaptive players having different emission reduction demands. In this research governments negotiate on the mitigation goals and whether or not to participate in the agreement. By applying game theory, the model allows for the formation of coalitions, cooperative solutions and free-rider behaviour.

A final element included in the system is the possibility of climate disasters. The relation between climate change and the occurrence of climate disasters can be explored in the model. Climate disaster can occur locally, affecting only specific countries. Climate disasters temporarily influence the climate change awareness or the amount of mitigation action of the governments and citizens that were affected by the disaster. This influence can either be positive, implying that climate disasters increase demand for mitigation action, or negative, implicitly implying that climate disasters increase demand for adaptation action, thus decreasing the demand for mitigation action.

Mitigation action emerges out of the actions and interactions of governments and citizens related to GHG emission reduction, influenced by their awareness of climate change, climate disasters and enforced mitigation action as a result of international negotiations on climate change response (illustrated in the right figure in Figure 1). The most important outcomes of the model describing the emergence of mitigation action are the cumulative GHG reduction and the annual GHG reduction relative to the initial value in the model. The model describes the time period of 2000 – 2100, with a time step of a year. The model consists of 5 governments and 100 citizens related to each government. Using this simplified representation of society, there is enough room to introduce heterogeneity amongst agents, yet it will be simplified enough to understand and explore the dynamics between those agents and feasible enough to conduct analyses given computational limitations.

2.2 Uncertainties influencing the emergence of mitigation action by society in the face of climate change

In order to construct internally consistent and plausible narratives about the pathways of the emergence of mitigation action by society in the face of climate change, uncertainties need to be acknowledged, identified, and their consequences need to be explored. We use four categories of uncertainties: uncertainties related to environment settings, agent settings, international negotiations on climate change response, and climate disasters. The main uncertainties related to the environment settings are the climate sensitivity and economic sensitivity of climate change. Uncertainties from the agent settings category are related to the adaptive traits governments and citizens apply in responding to climate change and factors influencing the interaction between governments and citizens. Uncertainties related to international negotiations on climate change response are factors influencing the internal mechanisms and frequency of these negotiations. Uncertainties related to climate disasters are factors influencing the internal mechanisms and stochastic factors behind the occurrence and effect of climate disasters.

The uncertainty space is specified in detail in Table 1. Some of these uncertainties are represented by an uncertainty range, representing a range of possible values that an uncertainty can have. For example the climate sensitivity and economic sensitivity of climate change have a range of possible values. Other uncertainties are represented as structural uncertainties, allowing switching between different model structures or categorical values of an uncertainty. For example, the model contains both a cooperative game theoretic representation of international negotiations, as well as a competitive game theoretic representation in the form of a repeated prisoner's dilemma. The left column displays the variable in which uncertainty is incorporated. The middle column describes the assigned uncertainty range for the parametric or structural uncertainties. The column on the right provides an explanation for the assigned uncertainty range.

Table 1: The uncertainties represented in the model

Uncertainty	Uncertainty range	Explanation and references
Environment settings		
Climate sensitivity and economic sensitivity of climate change factor 1	1.01 – 1.03	This factor influences the shape of the climate change impact equation. A low value of this factor represents a high climate sensitivity and economic sensitivity of climate change, and vice versa. The shape of climate change impact equitation is based on (IPCC, 2014; Nordhaus, 2007))
Climate sensitivity and economic sensitivity of climate change factor 2	0.80 – 1.20	See above explanation
Emission level change delay years	1; 3; 5	Governments and individuals take past years into account when adjusting GHG emission levels. Different delays are explored, ranging from a short delay (1 year) to a longer delay (5 years)
Agent settings		
Time horizon of governments	0 – 50	A time horizon of 0 relates to indifference about future climate change impact, whereas a time horizon of 50 could relate to thinking two generations ahead.
Time horizon of individuals	0 – 50	See above explanation
Standard deviation of time horizon distribution	0 – 20	A standard deviation is used to introduce heterogeneity in the individual time horizon of citizens of the same country. A value of 0 relates to a homogeneous distribution, whereas a value of 20 relates to a generation difference in possible distributions.
Democratic value of governments	0 – 1	The democratic value determines the extent to which governments base their mitigation policy on the interest of their citizens. A democratic value of 0 therefore relates to a complete stratocracy, whereas a democratic value of 1 relates to a complete democracy.
Future cumulative GHG prediction error	0 – 0.30	A prediction error is introduced to correct for the fact that governments and citizens do not have the capacity to correctly predict future cumulative GHG emissions. The prediction error ranges from 0 to 0.30, the latter indicating a 30% prediction error.
International negotiations on climate change response		
Years between international negotiations on climate change response	5; 10; 15	The frequency of major international negotiations on climate change response has been based on the Kyoto negotiations in 1997 and the Copenhagen negotiations in 2009. This research allows for more frequent or less frequent international negotiations on climate change response.
Game theoretic representation of international negotiations	Cooperative; Prisoners	Uncertainty exists about the game theoretic representation of the international negotiations on climate change response (Ackerman, DeCanio, Howarth, & Sheeran, 2009; Smead et al., 2014). The international negotiations can be of cooperative nature, in which governments seek a more shared solution for the problem. The international negotiations can also be of a more competitive nature in the form of a repeated prisoner's dilemma.
Mitigation enforcement factor	0.20 – 1	The strength of the mitigation enforcement that can be a result of international negotiations on climate change response can be altered, ranging from a relatively weak enforcement to a relatively strong enforcement.
Effect of international policy on citizens	0.50 – 1	The mitigation enforcement can have a different effect on citizens and national policy. The strength of this effect can range by adjusting this factor.
Effect of international policy on national policy	0.50 – 1	See above explanation.
Climate disasters		
Base chance of climate disaster	0.01 – 0.1	The chance that a climate disaster occurs, independent from the amplifying influence of climate change, can range between climate disasters occurring every year to every 10 years. This range has been based upon major climate disasters that have occurred that past decennia, of which some are accounted to climate change by some people.

Effect of climate change on climate disasters	0 – 1	The relation between climate change and the occurrence of climate disasters is under dispute (Weinkle, Maue, & Pielke Jr, 2012). This factor determines the strength of the relation between climate change and the occurrence of climate change. The influence of climate change on the occurrence of climate disasters is then subject to the strength of the relation and the amount of cumulative GHG emissions.
Initial severity of climate disaster	0 – 0.20	The influence that a climate disaster has on the climate change awareness of governments and individuals can range from 0 to 0.20.
Climate disaster memory	1; 3; 5	
Positive effect of climate disasters on climate change awareness	True; False	Scientific evidence on the direction of the effect of climate disasters on mitigation action is limited and in part contradictory. Some literature states that climate disasters have a positive effect on mitigation action (Rudman, McLean, & Bunzl, 2013; Spence, Poortinga, Butler, & Pidgeon, 2011; Zahran, Brody, Grover, & Vedlitz, 2006). Other literature states that climate disasters do not affect mitigation action (Dessai & Sims, 2010; Whitmarsh, 2008). Finally, there is also literature stating that climate disasters have a negative effect on mitigation action, because those struck by a climate disaster demand adaptation action, pushing mitigation action plans to a further future (Lemonick, 2012; Marshall, 2012). This ambiguity is captured in a structural uncertainty that allows the model to switch between a positive and negative effect of climate disasters on mitigation action.

3. Research method

To address the combined challenge of identifying narratives on the emergence of mitigation by society in the presence of various uncertainties, we apply an exploratory modelling approach to scenario development using agent-based modelling. Agent-based modelling enables capturing the complexity and emergence of mitigation action by society in the face of climate change (Gerst, Wang, Roventini, et al., 2013). To explore the consequences of the various uncertain factors, we use the agent-based model in an exploratory fashion (Bankes, 1993; Bankes, Walker, & Kwakkel, 2013). We generate series of computational experiments and assess the behaviour of the model across these experiments. To summarise these series of computational experiments in a small but representative set of scenarios, we use scenario discovery (Bryant & Lempert, 2010; Kwakkel, Auping, & Pruyt, 2013; Rozenberg, Guivarch, Lempert, & Hallegatte, 2014).

Scenarios provide a commonly used means to communicate and characterize uncertainty by bounding the ways in which the system under study could possibly evolve (van Vuuren et al., 2011). A conventional way of developing scenarios, following from the intuitive logics or scenario axis approach, aims at bounding the space of all plausible futures by developing a limited set of plausible scenarios. In this approach, one starts with specifying the decision that the scenarios are meant to inform. Next, the most important driving forces affecting this decision in the external environment are identified and scored in terms of their impact on the decision, and their degree of uncertainty. The set of highly uncertain, high impact driving forces form the scenario logic. Using the scenario logic, narratives of alternative internally consistent and plausible realisations of these driving forces are constructed, qualitatively or with the use of modelling and simulation (Bryant & Lempert, 2010).

The scenario logic approach to scenario development struggles if the system under study is subject to many interdependent uncertain factors (Lempert, 2003). That is, the scenario logic approach might fail to summarise the multiplicity of plausible futures into a small set of scenarios that fully represent all plausible futures (Bryant & Lempert, 2010). Moreover, the scenario logic approach relies on the mental models of the analysts. It has been found that the mental models which humans (consciously or unconsciously) use to deal with complex systems are typically event based, have an open loop view of causality, ignore feedback, fail to account for time delays, and are insensitive to non-linearity (Sterman, 1994). Hence, essential elements of dynamics in complex systems, namely feedback, time delays and non-linearity, cannot be appropriately dealt with. Consequently, mental simulations of complex systems are highly defective. This has been demonstrated empirically in various studies (Atkins, Wood, & Rutgers, 2002; Brehmer, 1992; Diehl & Sterman, 1995; Dörner, 1996; Kleinmuntz, 1992; Sastry & Boyd, 1998; Sterman, 1989). Therefore, Gerst, Wang, and Borsuk (2013) argue that rather than feeding scenarios to bottom-up models, scenarios should be derived from the ensemble of model simulations.

The ensemble of model simulations is generated through computational experimentation. These computational experiments systematically explore the consequences of alternative realisations of the various uncertainties (Kwakkel & Pruyt, 2013). This exploratory modelling approach can be used to analyse the consequences of uncertainty on many levels, ranging from parametric uncertainties to structural uncertainties (e.g. different structures and models). A given computational experiment describes one possible resolution to the various uncertain factors. By conducting many of these experiments, insight is generated into the behaviour of the model across the entire space of uncertain factors. To support this exploratory modelling, we have used the Exploratory Modelling Workbench developed by Kwakkel (2012).

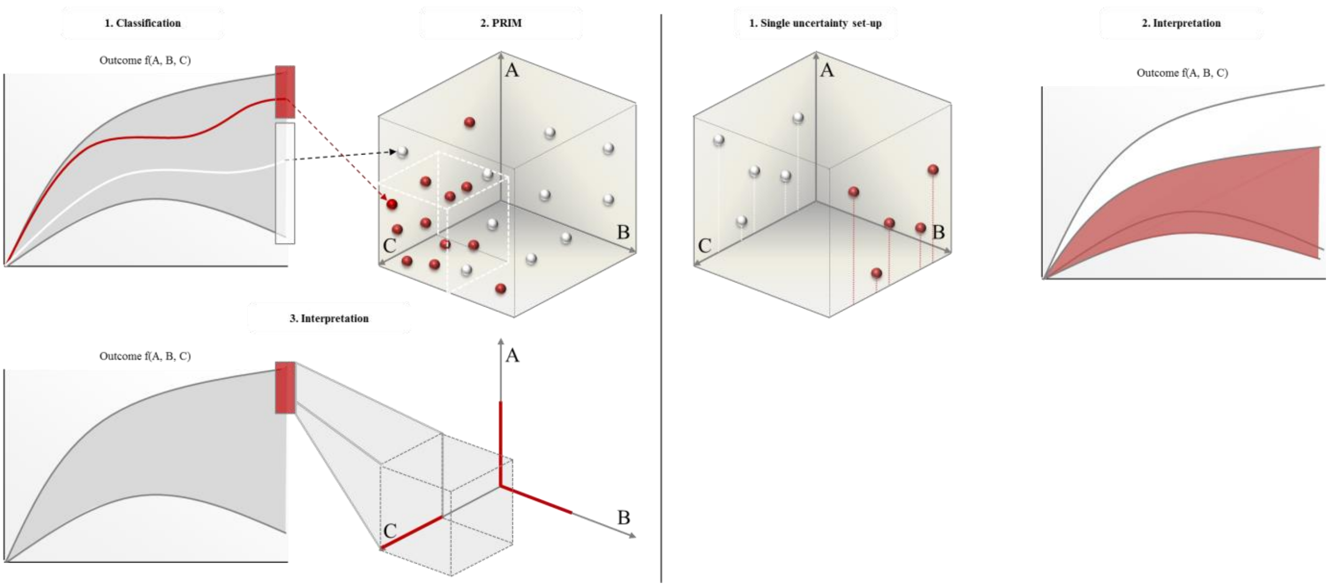


Figure 2: Visualisation of the PRIM analysis [Left] 1) A certain range of model outcomes is classified. 2) The PRIM algorithm selects a box with a high coverage and density of model runs that fall within the classification. 3) Parameter settings of uncertainties that are significantly present in the selected box are shown as a result.

Visualisation of the single uncertainty sensitivity analysis [Right] 1) Two sets of experiments are generated in which the settings of one uncertainty are fixed. The seeds of the experiments are made equal, so that the results can be compared. 2) By plotting the results of both sets, the influence of a single uncertainty can be explored.

The scenario discovery approach has been put forward as a technique that can be used for developing scenarios for problems that involve many uncertainties (Kwakkel et al., 2013). The goal of scenario discovery is to identify descriptions of the combinations of a small number of input parameters to a simulation model that are most strongly predictive of certain model outcomes (Lempert, Groves, Popper, & Bankes, 2006). In this research, scenario discovery is applied to identify narratives based on internally consistent and plausible assumptions on the emergence of climate change mitigation action by society. Based upon prominent scenario discovery literature (Bryant & Lempert, 2010; Lempert et al., 2006), the scenario discovery approach that has been applied used in this research consists of the following steps:

1. The key indicator or key indicators for the subject of the narratives are defined, in the case of this research being the emergence of climate change mitigation action by society. An agent-based model is constructed capturing the emergence of climate change mitigation action by society.
2. During the conceptual description of the research problem, the system conceptualisation and the model specification, uncertainties influencing the emergence of climate change mitigation action by society are explicitly acknowledged, identified and incorporated in the agent-based model.
3. The consequences of uncertainties are explored by conducting EMA. A large ensemble of plausible models is generated from the identified uncertainty space. By conducting explorative and targeted analyses over this ensemble of plausible models, the consequences of the various uncertainties influencing the emergence of climate change mitigation action by society can be explored. As a result, subspaces of the input space can be identified that are strongly predictive for the emergence of climate change mitigation action by society.
4. The identified subspaces of the input space can be translated into narratives. The number of relevant subspaces and narratives that are communicated are application specific.

In order to identify the subspaces, scenario discovery relies on rule induction algorithms. The most frequently employed algorithm is the patient rule induction method (Friedman & Fisher, 1999). PRIM aims at finding combinations of values for the uncertain input variables that result in similar characteristic values for an outcome variable. Specifically, PRIM seeks a set of subspaces of the uncertainty space within which the values of a single output variable is considerably different from its average value over the entire domain. PRIM describes these subspaces in the form of hyper rectangular boxes of the uncertainty space. An illustration of PRIM is displayed in the left figure in Figure 2. A second analysis used is the singe uncertainty sensitivity analysis. In this, a partial factorial design is made to explore the influence of single uncertainties on the full behavioural landscape. An illustration of the single uncertainty sensitivity analysis can be found in the right figure in Figure 2.

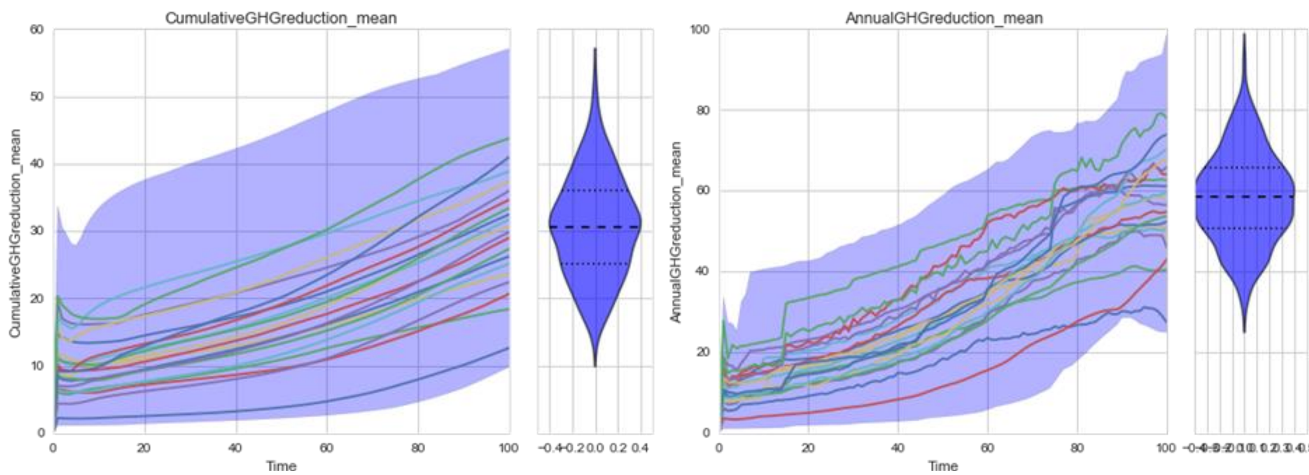


Figure 3: An envelope graph of the outcome range of 1000 experiments under the full uncertainty space of the model outcomes cumulative GHG emission reduction [Left] and the annual GHG reduction [Right]

In the analysis of the model, the full range of plausible model outcomes is mapped as a consequence of the deep uncertainties influencing the emergence of climate change mitigation action by society, displayed in Table 1. This explicit representation of the set of plausible model outcomes is made by conducting a large number of computational experiments. The EMA workbench, developed by Kwakkel (2012), supports generation of this large number of computational experiments and the analysis of the results. Using Latin Hypercube Sampling (LHS), a set of uniform samples of 1000 experiments has been generated over the multidimensional parameter space. Each of the 1000 experiments has to be replicated 100 times to correct for the stochastic uncertainty present in the model. This implies that in order to map the full uncertainty space, 100.000 model runs need to be executed. Conducting 100.000 model runs of the model used in this research on a 12 core processor takes about 3.5 hours to complete.

5. Model outcomes

In Figure 3 the envelope graphs of 1000 experiments, each replicated 100 times, for the model outcomes cumulative GHG reduction and annual GHG reduction are displayed. The cumulative GHG reduction is the most important indicator for the dynamics of the emergence of climate change mitigation action by society. The cumulative GHG reduction is determined by dividing the cumulative GHG emission by the cumulative GHG emission if no mitigation action would have been taken, that is, the business as usual GHG emission scenario. The annual GHG emission reduction is calculated in the same way. The annual GHG emission reduction is more easily interpreted, as it can be compared to existing emission reduction goals. However, because the annual GHG emission reduction can be temporarily affected at any point in time, it serves less useful for analysing the emergence of mitigation action over time. The blue shaded areas represent the minimum and maximum values of the model outcomes at any point in time. The large uncertainty space influencing the emergence of climate change mitigation action by society results in large differences in possible outcomes.

Using various types of analyses, the behavioural landscape of the emergence of climate change mitigation action by society has been explored. Using the single uncertainty sensitivity analysis, targeted exploration is conducted over the influence of uncertainties such as the time horizon of governments and citizens, the game theoretic representation of international negotiations and the effect climate disasters have on the demand for mitigation action. Two

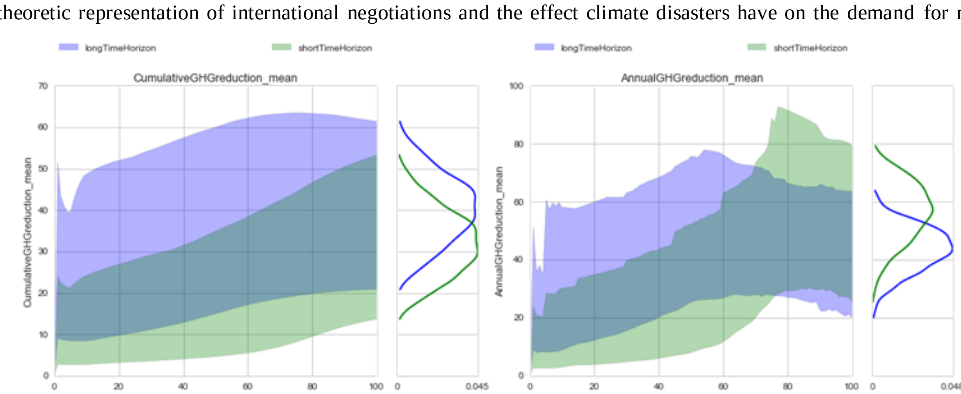
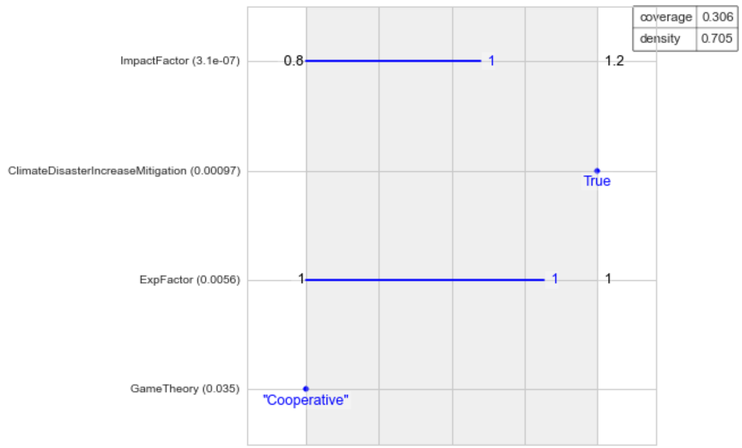


Figure 4: Single uncertainty sensitivity analysis on the influence of the time horizon of governments and individuals. The blue shaded areas represent experiments in which agents have a time horizon of 40 years. The green shaded areas represent experiments in which agents have a time horizon of 10 years.

Figure 5: PRIM analysis on a high cumulative GHG emission reduction



examples of these analyses are described below. For a complete overview of all analyses conducted on the exploration of the consequences of uncertainties influencing the emergence of climate change mitigation action by society, we refer to the MSc dissertation by Greeven (2015b) on this subject.

The single uncertainty sensitivity analysis in Figure 4 shows the influence of governments and citizens having a short versus a long time horizon. The blue shaded area represents the envelope graph of 1000 experiments under full uncertainty space in which governments and citizens have an average time horizon of 40 years. he green shaded area represents the envelope graph of 1000 experiments under full uncertainty space in which governments and citizens have an average time horizon of 10 years. It can therefore be concluded that the uncertainty related to the time horizon governments and citizens use to assess the future impact of climate change is important.

The PRIM analysis in Figure 5 shows the combination of subspaces in the input space of parameter settings that is considerably present in runs that end with a cumulative GHG reduction of more than 35% in the year 2100. The results of a PRIM analysis should always be interpreted as a combined result: a high cumulative GHG, of more than 235% in 2100, is significantly determined by states of the system in which there is a high climate sensitivity and economic sensitivity of climate change; in which climate disasters make governments and citizens increase their emission reduction behaviour; and in which cooperative game theory behind international negotiations on climate change response increases the chance of successful mitigation agreements.

By exploring the consequences of the uncertainties influencing the emergence of climate change mitigation action by society using both explorative and targeted analyses, subspaces of the input space have been identified that are strongly predictive for the emergence of climate change mitigation action by society. These subspaces can then be easily translated into communicable, internally consistent and plausible narratives. In this research we used only one axis to determine narratives, that is, the emergence of climate change mitigation action by society. Therefore, two narratives have been identified. The first narrative describes the emergence of strong climate change mitigation action. The second narrative describes the emergence of weak mitigation action. More narratives can be created by using multiple input or output indicators on the scenario axis. An example would be to identify four narratives: the emergence of strong mitigation action under a high and a low climate sensitivity and economic sensitivity of climate change, and the emergence of weak mitigation action under a high and a low climate sensitivity and economic sensitivity of climate change. One of the narratives identified in this research, using the scenario discovery approach supported by a combined application of ABM and EMA, is presented below.

Narrative: The emergence of strong climate change mitigation action by society

A strong emergence of mitigation action, measures by the amount of GHG emission reduction over the course of the 21st century, is mainly determined by the climate sensitivity and the economic sensitivity of climate change and the time horizon members of society apply in assessing their belief about required response. In the case of a strong relation between cumulative GHG emissions and climate change, a strong relation between climate change and the economic impact of climate change, and governments and individuals being able to assess the future impact of climate change far ahead, society's response to climate change will be characterised by high annual GHG emission reductions in the start of the 21st century. Society is concerned about the future impact of climate change which results in a high climate change awareness. Stimulated by their citizens, governments are more willing to cooperate in tackling the problem of climate change in the international arena. Furthermore, they intend to be cooperative in the negotiations with the aim of taking collective responsibility for this global problem. International negotiations on climate change response will take place frequently and the mitigation agreements resulting from these negotiations consist of stronger mitigation goals. Finally, the potential impact of climate change is becoming visible through the occurrence of climate disasters. This results in an increase in climate change awareness highlighting the importance of taking mitigation action. International negotiations on climate change response that happen to be right after the occurrence of a climate disaster will even have an increased chance to be successful and result in stronger mitigation goals. In conclusion, this narrative describes a scenario in which climate change is serious, but a conscious society is aware of the future impact climate change can have and is prepared to respond with strong mitigation action.

7. Conclusion and recommendations for further research

In this research we have conducted a scenario discovery study that enabled the identification of internally consistent and plausible narratives on the pathways of the emergence of climate change mitigation by society. The scenario discovery approach is supported by a proposed modelling approach combining agent-based modelling and exploratory modelling and analysis. The various uncertainties influencing the emergence of climate change mitigation action by society have been acknowledged, identified and their consequences have been explored. As a result, two narratives have been constructed, describing how certain sub-spaces of the uncertainty space lead to the co-evolutionary emergence of strong and weak mitigation action.

The narratives constructed in this research are based on a model-based exploration of the consequences of uncertainties influencing the emergence of climate change mitigation action. The large difference between the two narratives shows the consequences of the large uncertainty space influencing the emergence of climate change mitigation action by society. The research therefore highlights the importance of uncertainties and ambiguities such as the ones related to the time horizon members of society apply in assessing the future impact of climate change, the internal mechanisms behind international negotiations on climate change and the influences of climate disasters on climate change response. Constructing narratives in such an open, objective and exploratory way can help in conveying the consequences of uncertainties influencing society's response to climate change. This research can therefore serve as a though-provoking stimulus for analysts or decision makers to be aware of the many possible pathways of society's response to climate change and to take the consequences of uncertainties into account.

Further research could be aimed at improving the agent-based model on the emergence of mitigation action by society in the face of climate change. Major improvements at the model could be made related to the interplay between climate change mitigation and adaptation, as the mere focus in this research has been placed on the emergence of mitigation actions. Furthermore, heterogeneity among agents can be extended. A potential area for introducing heterogeneity is regarding the impact of climate change on governments and citizens. Next, the cognitive behaviour of agents in the model could be further investigated. Other factors influencing the adaptive traits of agents determining their response to climate change such as social influence can be investigated. Finally, other scenario discovery studies could further test and enhance the proposed agent-based scenario discovery study.

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