APPLYING THE CONCEPTS OF CRITICAL TRANSITIONS AND THE TRAGEDY OF THE COMMONS TO THE ENERGY SYSTEM – AN AGENT-BASED APPROACH

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I. PREFACE

With the writing of this master thesis I am finalizing my student time. It has been a great privilege being a student at Utrecht University and having the opportunity to learn and meet new people. My student life has been full of ups and downs. I would like to consider this final product as a team effort of everyone who has helped me in some way, small or big. I hope you enjoy reading this thesis and that it in some way will make a small contribution to society.

II. ACKNOWLEDGEMENT

I would like to thank my supervisors for their help with writing this thesis; Gert-Jan Kramer for his excellent remarks on how to improve the model, which really made a big difference and I would never have thought of myself. Oscar Kraan for his enthusiasm and positivity about the project and for the many fun and helpful discussions. Besides, I would like to thank friends and family for their interest, advice and support for this research.

III. Summary

There is a need for models that describe non-rationality of agents and complexity regarding the energy transition. Agents-based modelling is a well-suited method to do this. The research question is:

What can we learn from simple agent-based models about the effects of behavioral dynamics of individuals on the energy transition, using the concepts of critical transitions and the Tragedy of the Commons?

Two existing models are adapted to answer this research question.

The first model (Scheffer, Westley, & Brock, 2003), is a model about critical transitions in public attitude regarding a problem. These sudden shifts are caused by a cost of deviation from other individuals. The critical transition model is adapted to the Agent-based Critical Transition (ACT) model with social networks, heterogenous agents, leaders and continuous attitudes of agents.

The second model (Schindler, 2012), is an agent-based model of the Tragedy of the Commons, which describes the overuse of grass by herdsmen who own cows. The model is adapted and extended to the Agent-based Tragedy of the Commons (AToC) model by introducing incomplete information of the state of the grass and a heterogeneous level of environmentalism of the herdsmen.

The ACT model showed arguments that the change in attitude regarding climate change will be a smooth transition. First, individuals are often influenced by their peers and not the average attitude of society. Second, there are opinion leaders available regarding climate change. Third, small steps of progress in the energy transition are possible. However, there are also arguments that there will be inertia and a sudden shift in attitude regarding climate change. First, vested interests regarding fossil fuels may influence society. Second, society may act out of habit, limited cognitive resources and imitation.

The AToC model showed that the slow ability of society to adapt may contribute to a tragedy regarding climate change. Besides, it showed that different perceptions of the state of the grass and heterogeneity in the level of environmentalism caused herdsmen to act heterogeneous. In the same way, countries may perceive climate change differently and therefore some countries may be leaders in action while others are free-riders. Lastly, cost of deviation caused the herdsmen to act more like the average herdsmen. This can be explained as the tendency to act out of habit, imitation and on limited cognitive resources of society. This increases the likelihood of a tragedy.

TABLE OF CONTENTS

IV. LIST OF FIGURES

V. LIST OF TABLES

VI. LIST OF ABBREVIATIONS

ABM	Agent-based modelling
ACT	Agent-based Critical Transition model
AToC	Agent-based Tragedy of the Commons model
CAS	Complex adaptive system
MASTOC-s	Multi-Agent System of the Tragedy of the Commons (Schindler)
ToC	Tragedy of the Commons

1. INTRODUCTION

An international climate agreement was made on COP21 in Paris in 2015 where countries agreed to keep global warming below two degrees Celsius (United Nations Framework Convention on Climate Change, 2015). Although there is scientific consensus that action is needed it is uncertain whether society will act accordingly. Normative studies show scenarios where the window for achieving this Paris agreement is rapidly closing (Rogelj et al., 2015). Exploratory studies show widely different scenarios but agree that reaching the 2 degrees Celsius goal requires exceptional effort (World Energy Council, 2016). These studies are often dominated by a techno-economical paradigm and do not take the human factor into account (Bale, Varga, & Foxon, 2015; Hawkes, 2015). The limitations of this is that agents rarely act economically rational (Jager, Janssen, De Vries, De Greef, & Vlek, 2000). Real agents may lack perfect information and may act differently due to for example peer influences or environmental concern. The real behavior is not accurately represented by simple cost optimization decision rules.

Besides that, the energy system is a complex adaptive system (CAS) (Bale et al., 2015). CAS are systems with many constantly interacting dynamical agents, where the control is highly decentralized (Bollinger, Davis, & Nikolic, 2013). The many interactions between the agents cause the overall system behavior. With its many interacting and heterogeneous agents (consumers, policy makers, companies) the energy system is an example of a complex system. When modelling complex adaptive systems in a techno-economical way, a reductionist view with the emphasizes on analyzing the components separately is used (Kupers, Faber, & Idenburg, 2015). However, CAS cannot be understood by analyzing the separate parts because the system behavior is larger than the sum of its parts. The dynamics of a complex system are caused by the structure of the connections between the sub-systems and not by understanding the individual parts. So, a complexity view is used instead of a traditionally scientific reductionist view.

Agent-based modelling (ABM) is a well suited method for modelling complex adaptive systems and human behavior, such as the energy system (Bollinger et al., 2013). It is an approach to model dynamical processes that involve autonomous agents with their own characteristics (Macal & North, 2005). ABM is used for finding the overall system behavior by specifying the rules for the individual agents. In these rules is described how the agents influence each other and how they relate to the environment in which they live.

However, ABMs that are too complex are not transparent enough and tend to be a black-box and ABMs that are too simple models do not represent the complexity of a system enough. A successful model of a CAS is a CAS itself, which can be easily made too complex to provide insight (Bollinger et al., 2013). The model must also characterize the system and show important dynamics regarding the research question. So, there must be a balance between being complex enough and simplicity. Besides this, the model must have an interesting relationship with the energy transition. Two models show found in literature show an interesting relationship with the energy transition and have the potential for being complex enough while being understandable.

Scheffer, Westley and Brock (2003) made a simple mathematic model of critical transitions in public opinion, which are sudden shifts in the aggregated opinion from individuals. The model considers the effects of peer pressure and the perceived severity of the problem. Based on this model, Scheffer et al. (2003) describe four factors that influence the transition trajectory of social systems: peer pressure, absence of leaders, complexity of the problem and homogeneity of the population.

This model fulfills the requirement that it can show interesting dynamics regarding the energy transition. In order to reach the Paris goal the UN emphasizes that a radical transition is needed, rather than merely a fine tuning of current trends (UN, 2015). Consumer behavior is seen as important for such an energy transition (IPCC, 2014). Critical transition theory (Scheffer, 2009) can be used to model such a radical transition of consumer behavior regarding energy use. However, the critical transition model does not describe actor behavior but uses a mean-field approach. Therefore, this model is adapted into an agent-based model called ACT (Agent-based Critical Transition model).

The other model is an ABM of the Tragedy of the Commons (Schindler, 2012). In this model, there are herdsmen who own cows on a pasture with a finite amount of grass. Each herdsman decides to add or remove cows based on their social-psychological dispositions like selfishness, collaboration, fairness or conformity. However, the model is more focused on the Tragedy of the Commons. Therefore, the model is adapted to show more interesting dynamics regarding the energy transition. This is done by making the link between the grass on the pasture as the carbon budget of the earth.

The goal of these two newly created models is to explore building blocks of narratives that are consistent with the results of the ABMs. The models are compared to the energy transitions and to each other, to see commonalities. These are the research questions:

Main research question:

What can we learn from simple agent-based models about the effects of behavioral dynamics of individuals on the energy transition, using the concepts of critical transitions and the Tragedy of the Commons?

Sub-questions:

1. How can we relate Scheffers's critical transition model to the energy transition by replicating and extending the model using agent-based modelling?
2. How can we relate Schindler's Tragedy of the Commons model to the energy transition by adapting and extending the model using agent-based modelling?
3. How can the results of the agent-based models be explained in relation to the energy transition?
4. How do the insights regarding the energy transitions compare between those models?

These research questions are answered by building ABMs of these two models. These ABMs are used for exploring potential building blocks of a narrative regarding the energy transition.

2. BACKGROUND

2.1 Agent-based modelling

Why modelling?

Simply put, a model is a simplification of reality (Booch, Rumbaugh, & Jacobson, 2005). The model gives the relevant aspects for the chosen type of abstraction. One fundamental reason for modelling is to better understand the system that is developed. When a system becomes larger and more complex, modelling becomes more important because we cannot comprehend complex systems in its entirety. Simple models may be valuable even if they are not exactly “right” in an engineering sense (Epstein, 2008). They do this by capturing the qualitative behavior of interest.

Agent-based modelling

Agents-based modelling (ABM) is a framework to simulate the behavior of agents (Macal & North, 2005). An agent can represent many things. The most used ones are people or groups of people. During the simulation, an agent interacts with other agents and the environment. The environment contains all the information outside the agent and provides the structure in which the agents interact with each other. The interactions change the parameter settings of the agent. These happen according to the modelled rules of the ABM. All these interactions together cause the overall system behavior (Bollinger et al., 2013).

Agent-based modelling in societal problems

Agent-based modelling provides decision support in problems (Bollinger et al., 2013). It is used for simulating possible realistic outcomes of a problem, before the system is actually created (Bollinger et al., 2013). ABM is previously used in a wide range of topics (Macal & North, 2005). In a business context, these application can be classified in four areas: flows (e.g. traffic), markets (e.g. stock market), organizations (e.g. operational risk) and diffusion (e.g. innovation diffusion) (Bonabeau, 2002). One of the motivations for creating ABMs is the capture of the emergent behavior, which is the overall system behavior of a complex adaptive system (Bonabeau, 2002). The interaction of the individual components causes the emergent behavior. The behavior of the individual components alone, do not have the same properties as the emergent behavior.

2.2 Critical transitions theory

Basically, a critical transition is a sudden shift from one stable state to another stable state once a threshold is passed (Scheffer, 2009). First, there is explained the interest in critical transition regarding the energy transition. Then, there is elaborated on what a critical transition is. After that, a critical transition model found in literature is explained and the relationship of it with the energy transition.

Why a simple ABM of critical transitions?

Originally, these models of critical transitions come from the field ecology. However, these same dynamics can also be applied to social problems (Scheffer, 2009). There is a large bandwidth of possible scenarios regarding climate change and the pace of mitigation is widely discussed. So, the question is what is the pace of the energy transition. Critical transition may give insight in this by answering to what extent critical transitions may occur. It can show the possibility of non-linearities in the transition towards sustainable energy. Besides, literature shows evidence of the occurrence of critical transitions in society and shows elements that cause critical transitions, which is explained in the next paragraph.

Evidence for critical transitions and elements that affect transitions

There is evidence of the occurrence of critical transition in society and for feedback mechanisms that cause the critical transition. For example, Gladwell (2006) describes several case studies of sudden shifts in society. To create such a sudden shift, people must become more likely to adopt a behavior the more widespread it is. This creates a virtuous cycle of the new behavior. Three different kind of mechanisms that may cause a virtuous cycle of new behavior are described.

A modest social feedback may create a radical transition (Nyborg et al., 2016). There is evidence of social influence due to peer pressure (Asch, 1955), social norms (Goldstein, Cialdini, & Griskevicius, 2008) and contagion in behavior (Christakis & Fowler, 2009). Observability increases these social effects (Nyborg et al., 2016).

Another feedback is that a consumer's good increases in value when other consumers buy it (Nyborg et al., 2016). For example, if only a few people have electric cars, there will be few electric charging stations. However, if a lot of people have electric cars, the amount of electric charging stations rises, which increase the value of electric cars.

Lastly, if leaders become active they can catalyze the critical transition by mobilizing groups to change (Gladwell, 2006). These leaders are well connected and have high charisma to cause emotional contagion.

What are critical transitions?

Critical transitions are sudden shifts from one stable state to another stable state in a system if a threshold is passed (Scheffer, 2009). A stable state is a dynamical equilibrium, towards which the system gravitates. Figure 1 is a representation of a system with two stable states. If the system is in the stable state above and close to the threshold *F2* and the conditions change slightly, a critical transition occurs towards the lower stable state. To get back towards the above stable state the conditions must change towards threshold *F1*, then a critical transition happens in the opposite direction. The pattern in which forward and backward shifts occur at different locations is known as hysteresis (Scheffer, 2009). The dotted line in the middle are unstable equilibriums. A slight perturbation from the unstable equilibriums leads towards a shift towards another equilibrium because there is positive feedback loop to move away from it.

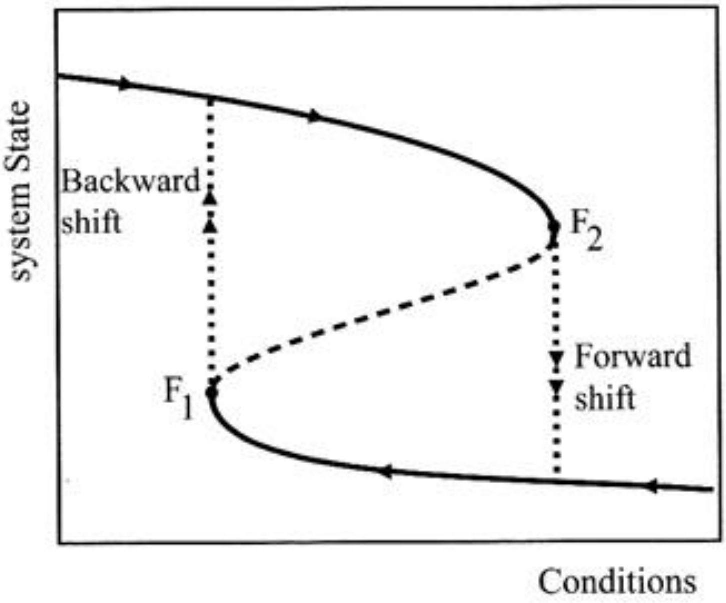

Figure 1: A critical transition in a system (Scheffer, 2009). When the conditions reach tipping point F1 or F2 there is a sudden shift towards another stable state.

Mathematical model of critical transitions in public opinion

Scheffer et al. (2003) developed a mathematical model of critical transitions in public opinion (see appendix A1). It is a simple model for investigating inertia and sudden shifts in public opinion (or attitude) due to social pressure. In this model, the individuals have two modes of opinion regarding a problem: active or passive. Each individual has a chance of being active or passive depending on their individual desire to be active and the effects of peer pressure. The peer pressure uses a mean-field approach. This means that the amount of peer pressure depends on the deviation from the average opinion of all other individuals. Differences in desire to be active are modelled by a stochastic component and the law of large numbers. This means that when it is assumed that when many individuals are modelled that the average public opinion becomes close to the expected value.

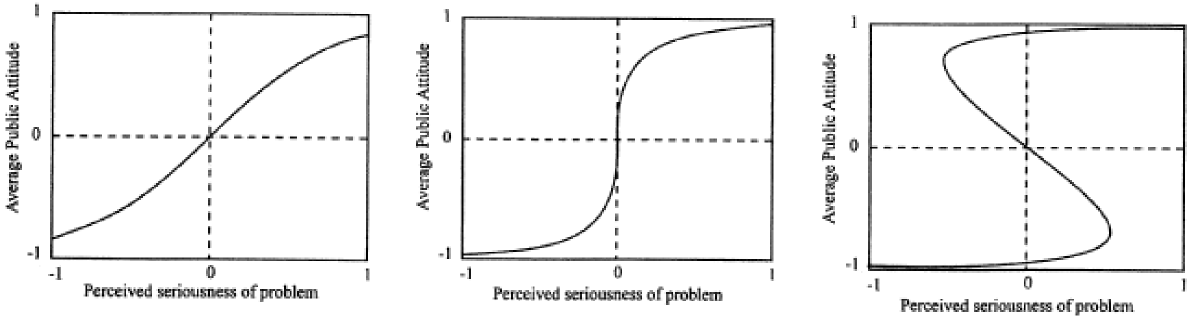

Figure 2 Transition trajectories for low (left), medium (middle) and high cost of deviation (right).

Implications of the model

Scheffer et al. (2003) predicts that peer pressure, absence of leaders, complexity of the problem and homogeneity of the population causes hysteresis, based on this model and literature research (see Figure 3). When these elements are high, it is predicted that despite the severity of the problem no action will be taken until a sudden point when a critical transition takes place. The explanation of this is that a lot of peer pressure causes the population to conform to the status quo. When a few people start becoming active, others start to join and this eventually leads to a critical transition. This effect is increased when there are no leaders, the complexity of the problem is high and the population is homogenous.

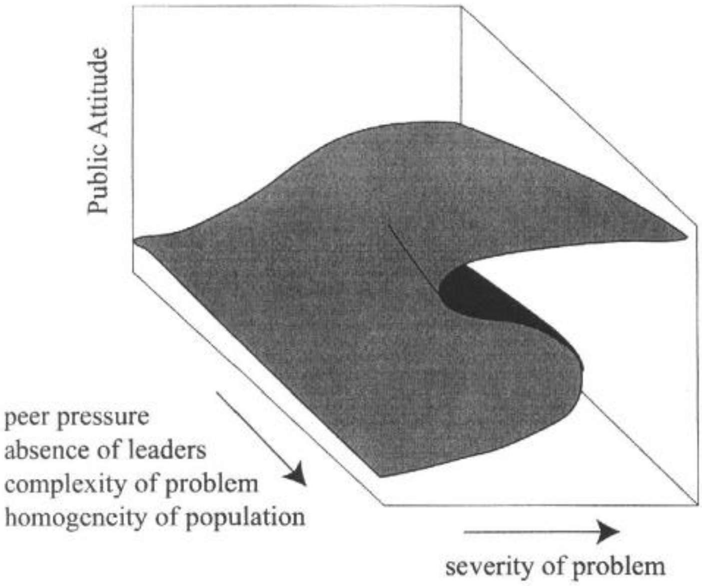

Figure 3: The outcome of the model of Scheffer (2009) is plotted in this figure. He predicts that the public attitude has the same characteristics for peer pressure, absence of leaders, complexity of the problem and homogeneity of the population.

Critical transition theory and the energy transition

These same dynamics of inertia, non-linearities and sudden shifts can also describe the trajectories of the energy transition. For example, with low peer pressure there is an almost proportional action taken compared to the perceived seriousness of climate change. However, when there is higher peer pressure, there is more initial inertia and then a sudden change towards action. Other elements as described by (Scheffer et al., 2003), like leadership and heterogeneity of the population also relate to the energy transition. These dynamics can be used for building blocks of narratives of the energy transition.

The original critical transition model describes three components: average public attitude, perceived seriousness of the problem and a cost of deviating from the overall group tendency. The average public attitude is the opinion whether action should be taken regarding a problem. The cost of deviation is assumed to be due to peer pressure between agents.

Regarding climate change, the perceived seriousness of the problem, it the opinion of people about how serious climate change is. The cost of deviation regarding climate change is the cost to deviate your attitude from the average attitude. This can be due to vested interest, social influence like peer pressure, contagion in behavior or social norms, habit or advantages of large scale use of a certain product. The average public attitude represents the average attitude of individuals regarding whether climate action should take place. A critical transition means that there is a lot of inertia until finally climate change is very severe and people change attitude. While a smooth transition is a transition where early action is taken.

2.3 Tragedy of the Commons

Basically, the Tragedy of the Commons describes how a collective resource gets overused by individuals. Individuals gain profit by using the resource while the cost of overusing is shared by all. First, there is explained why this model is used in this research. After that, the Tragedy of the Commons is explained more elaborately. Then, the model of the Tragedy of the Commons used in this research is described shortly. Lastly, the relationship between this model and the energy transition is described.

Why a simple ABM of the Tragedy of the Commons?

The Tragedy of the Commons can be made a simple model, which can give insight in when action is taken regarding a problem. Although, the original narrative is about herdsmen, cows and grass the same dynamics can be applied to the energy transition. The grass is a common pool resource and so is the carbon budget. Besides, the Tragedy of the Commons is a widely known narrative, which is researched a lot.

Tragedy of the Commons

The Tragedy of the Commons was first discussed in 1968 by Garret Hardin (Hardin, 1968)**.** He envisioned a pasture open to all. The herdsmen consider whether they want to add one animal to their herd. On the one side, this helps get them more profit. But on the other side, this leads to overgrazing. However, the cost of overgrazing is divided by all the herdsmen on the pasture. Therefore, the utility of adding an animal is bigger than keeping the same herd size. Every herdsman trying to maximize their gain will constantly add animals. However, this ultimately leads to an overgrazed pasture. This is the Tragedy of the Commons. Each herdsman is inclined to keep adding animals although the capacity is already exceeded. This is because to maximize short-term profit the herdsman must increase animals because the cost of overgrazing is shared by the other herdsmen (Ostrom, 2008). In the Tragedy of the Commons the herdsmen are assumed to be short term oriented, profit-maximizing, have perfect information, and they have the same assets, skills, discount rates and cultural views (Ostrom, 2008).

Management of common pool resources

The grass of the pasture is an example of a common pool resource. Common pool resources are finite and it is difficult to exclude people from using it. Elinor Ostrom came up with a theory for governing the commons (Ostrom, 1990). She states that the Tragedy of the Commons is only right when there is a large group, no one communicates and there do not exist rights to the resource (Ostrom, 2008). In the other case, the herdsmen can self-organize and create rules. The likelihood that this happens is dependent on: a low discount rate, homogeneous interest, the cost of communication is low and the cost of reaching an agreement is low (Ostrom, 2008). Once there are rules according to Ostrom, many will follow them in case they belief others do so too.

Model Tragedy of the Commons

In the literature, there already is an ABM of the Tragedy of the Commons (Schindler, 2012). It describes the behavior of herdsmen on a pasture with cows. The grass, which is the common pool resource, can be depleted. In the model, each herdsman is given social-psychological dispositions. When the herdsmen are short-sighted and profit maximizers the pasture is unsustainably managed as predicted by Hardin's original Tragedy of the Commons. However, the dispositions fairness to others, positive reciprocity and risk aversion are positively related to sustainable management of the pasture.

Tragedy of the Commons and the energy transition

The Tragedy of the Commons can be related to global warming. In the originally paper by Hardin the common pool resource is grass. Regarding climate change the common pool resource is a healthy climate. Another way to describe it, is that the atmosphere is a common pool sink. Humans make individual benefit by using fossil fuels but they harm the total environment by adding greenhouse gases to the common pool sink. However, the price of adding greenhouse gases to the common pool sink is shared by all inhabitants of the world. The herdsman in the Tragedy of the Commons by Hardin can have social-psychological dispositions like selfishness, collaboration, fairness and conformity. This is the same for countries. They all have different social-psychological dispositions regarding climate change. An analogy can be made between the grass in the Tragedy of the Commons and the carbon budget at the global warming problem. Both are the common pool resources, which are used by individuals who are looking for short-term individual benefit.

3. METHODS

In this research, behavioral dynamics of individuals regarding the energy transition are investigated. This is done to get more insight regarding possible pathways of the energy transition. Therefore, two new models are created. The newly created models must fulfill the following requirements:

1. They must have a link with the behavioral dynamics regarding the energy transition.
2. They must have a good balance between simplicity and being enough representative for the behavioral dynamics which occur in reality. So, although a model must be simple enough to understand it. It must at the same time represent the essential elements of the behavior we are interested in.
3. The models must be agents-based models, so they can specify agent behavior to incorporate non-rationality and a complexity view.

To do this, two already existing models are adapted to fulfill these requirements. These are a simple model of critical transitions in public opinion (Scheffer et al., 2003) and an ABM of the Tragedy of the Commons (Schindler, 2012). The results of experiment done on these newly created models are interpreted for narrative elements regarding the energy transition. All the agent-based modelling is done by using the software package Netlogo. The results of the agent-based model will be opened in the software package R (R Development Core Team, 2015), which is used for statistical computing and graphics. The model descriptions can be found in appendix B and appendix E.

4. AGENT-BASED CRITICAL TRANSITION (ACT) MODEL

4.1 Missing elements and adaptations critical transition model

A few elements were missing to fulfill the requirements of the new model. Table 1, summarizes the missing elements and the adaptations needed.

Table 1 Properties of critical transition model Scheffer, requirements ACT model and properties of the energy transition

Scheffer	Requirements	Energy transition
Cost of deviation by mean-field	Networks	Social influences by peers
Heterogeneity in attitude using law of large numbers	Heterogeneity in attitude by explicitly modelling	Heterogeneity in attitude regarding climate change
No leaders modelled	Leaders modelled	Leaders in the energy transition
Passive or active attitude	Possibility to have neutral attitude	Continuous attitude regarding climate change possible

Mean-field to networks

The original model uses a mean-field approach. When a model assumes mean-field interaction it tends to smooth out fluctuations (Bonabeau, 2002). ABMs can show dramatically different results then a mean-field approach. It describes the social and physical networks of the agents instead of using a mean-field approach. This can for example, show the effects of clustering of agents, which a mean-field approach cannot. In the energy transition, there could be for example clusters of individuals who adopt solar panels.

Therefore, the model is adapted to an ABM. In this ABM, the agents have a social network and only are influenced by their peers instead of the average public attitude. By doing this a more realistic effect of social influences can be shown.

Explicitly modelling heterogeneity in attitude

Originally, the heterogeneity in attitude regarding a problem was modelled by using the law of large numbers. The drawbacks of this method are that it is not transparent, it does not give insight in the effects of randomness, and the distribution of utility to get active or inactive cannot be easily changed.

In the ACT model heterogeneity in attitude is modelled by giving each agent a different utility of getting active. Explicitly modelling this helps building consistent stories between the results and the explanation.

No leaders to leaders

Although Scheffer predicts the effects of heterogeneity of individuals to influence the transition trajectory, it is not explicitly modelled in his model.

Therefore, in the ACT model leaders are modelled which have more influence than other individuals. In this way, the effect of leaders can be made more explicit and checked for consistency between model results and the explanation of the effects of leaders.

Binary towards continuous attitudes

The original model assumes that the individuals have a binary attitude regarding a problem, active or passive. However, real individuals do have a more continuous attitude.

Therefore, the ACT model does also have the option of a neutral attitude. Although, this is not fully accurate, it is more representative for reality.

4.2 Conceptualization

The model consists of 250 agents, which represent abstract individuals. Each individual has an opinion regarding a problem, which can be active or passive. The individuals do have a physical location on a 10 x 25 grid. Each individual has a utility for having an active opinion and one for a passive opinion. They feel a cost for deviating from the average public opinion, which is called the peer pressure sensitivity.

This model is extended with a few elements. The individuals are given a social network. Now, they feel a cost of deviation towards their social network instead of the average public opinion. Another extension is that the individuals can have a neutral opinion and have a utility for being neutral. Finally, the agents can be a leader, which have more peer pressure on others.

4.3 Narrative

The complete model description and Netlogo implementation can be found in appendix B.

Initialization

First the model is initialized. 250 individuals are created in the model and given a physical location on a 10 x 25 grid. Each of them is initialized with an inactive opinion. Besides, each of them is given a utility to be active and a utility to be passive. Every agent gets the same peer pressure sensitivity.

There are a few ways in which the model is extended. The individuals can get a social network of connections with other individuals, the option of agents to be leaders with more influence, or the agents get also a utility for having a neutral opinion.

Experiment runs

After the initialization, the experiment is executed. During the whole experiment, the utility for being active of the agents is linearly increased from their initial level and then linearly decreased back to their initial level at the end of the experiment. After each small change in the utility for being active the agents decide whether they will have an active or passive opinion regarding the problem. They decide this based on the cost of deviation towards the average public opinion and their utility for having an active opinion.

When the agents are initialized with a social network they don’t decide based on the average public opinion but based on the average opinion of their peers in their social network. In case there are leaders, the agents look at a weighted average public opinion, where leaders have a higher weight. Lastly, when individuals can also have a neutral opinion, the individuals can decide to take an active, neutral or passive opinion.

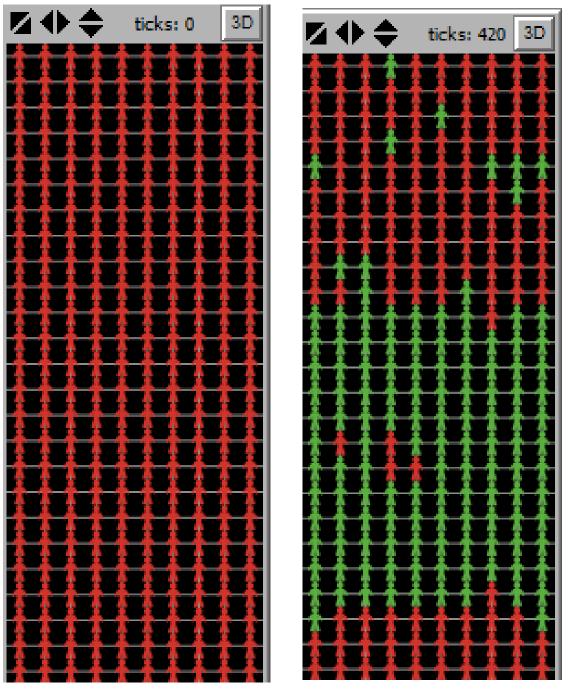

Figure 4: In the left figure, the model is initialized with all individuals having a passive opinion and their social network are the 4 individuals closest to them. In the right figure, the utility for having an active opinion is increased and some individuals decided to have an active opinion regarding the problem.

Explanation narritive

The utilities for an active opinion are increased and then decreased to see whether hysteresis occurs. Hysteresis is discussed in paragraph 2.2. In this way, there can be looked at when there is a tipping point when the individuals are initially passive and when the individuals are initially active. There is hysteresis when these tipping points differ.

4.4 Differences with original critical transition model

Mean-field approach to agent-based model

In Scheffer's mathematical model, the probability of having an active and passive opinion are computed with equation 1 and 2.

$$P(+) = \frac{e^{\frac{U(+)-c(1-A)^2}{s}}}{e^{\frac{U(+)-c(1-A)^2}{s}} + e^{\frac{U(-)-c(-1-A)^2}{s}}} \tag{1}$$

$$P(-) = \frac{e^{\frac{U(-)-c(-1-A)^2}{s}}}{e^{\frac{U(+)-c(1-A)^2}{s}} + e^{\frac{U(-)-c(-1-A)^2}{s}}} \tag{2}$$

Table 2 Explanation of the parameters used by Scheffer.

Parameter:	**Explanation:**
$P(+)$ and $P(-)$	Probability of having an active of passive opinion of an individual
$U(+)$ and $U(-)$	Utility of having an active or passive opinion of an individual
C	Peer pressure sensitivity
S	Scaling factor for heterogeneity in the utility of having an active or passive opinion using the law of large numbers
A	Average public opinion

In equations 1 and 2, A is the average public opinion. In the ACT model, the A is changed by the average opinion of the peers of the individual.

Heterogeneity using law of large numbers to distribution of utility for active opinion

The original model uses the law of large numbers to incorporate heterogeneity in the utility for being active. This law states that the result of a lot of trails should be close to the expected value. In this case it means that when there are a lot of individuals with heterogeneous utilities, the average probability of an active opinion is equal to above. In the equation the factor s, states the size of the heterogeneity in the utilities of the individuals.

However, in the ACT model the utilities of the agents are explicitly defined. This is done by using a probability function for what the utility of being active is for each agent.

Active or passive opinion to active, neutral or passive opinion

The equations for the probability of having an active or passive opinion are stated before. The new equations, when an individual can also have a neutral opinion, are stated below.

$$P(+) = \frac{e^{U(+)-c(1-A)^2}}{e^{U(+)-c(1-A)^2}+e^{U(0)-cA^2}+e^{U(-)-c(-1-A)^2}} \qquad (3)$$

$$P(0) = \frac{e^{U(0)-cA^2}}{e^{U(+)-c(1-A)^2}+e^{U(0)-cA^2}+e^{U(-)-c(-1-A)^2}} \qquad (4)$$

$$P(-) = \frac{e^{U(-)-c(-1-A)^2}}{e^{U(+)-c(1-A)^2}+e^{U(0)-cA^2}+e^{U(-)-c(-1-A)^2}} \qquad (5)$$

When the average public attitude is passive, it is easier to become neutral than active. This is because the cost of deviation is smaller for neutral then.

No leaders to leaders

Scheffer mentions the effects of leaders as explained in paragraph 2.2, but does not explicitly model it. In the ACT model, leaders can be incorporated. Without leaders, the average public opinion of the ACT model is calculated by equation 6.

$$A = \sum_i \frac{\text{opinion}_i}{total\ individuals} \tag{6}$$

When leaders are included this is calculated by equation 7.

$$A = \sum_i \frac{\text{opinion}_i * \text{leadership}_i}{\text{total individuals}} \tag{7}$$

In equation 7, leadership is 1 for normal individuals and for leaders it is higher.

4.5 Experimental setup

Several experiments are conducted on this model. The parameter settings for each of these experiments can be found in appendix C. The experiments are repeated at least 5 times to create a confidence interval. From these experiments, the median is calculated and a 100% confidence interval. After looking at the results, it could be seen that 5 repetitions created a reliable confidence interval because for each iteration the results looked similar.

Reproduction of the mean-field approach

The first experiment is a verification of the results of Scheffer. In this experiment, the same model as Scheffer is used but in an ABM environment. The purpose of this experiment is to make sure the model can be accurately reproduced.

The other experiments are elaborations on the model of Scheffer.

Peer pressure in lattice network

In this experiment, there is peer pressure by other agents in a lattice network instead of being influenced by all the other agents. As can be seen in figure 5, the agent does have four connections with his neighbors. The agents on the borders of the 10 x 25 grid do also have four connections because the 'world' created in the agent-based model wraps horizontally and vertically. The purpose of this experiment is to see the effects of a social network on the transition trajectory. For example, what the effect of this lattice network is on the possibility of a critical transition.

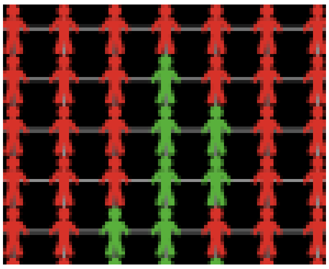

Figure 5 In a lattice network or nearest neighbor network the agents have connections with their four closest neighbors.

Heterogeneity in perceived severity of the problem

Here, the effects of heterogeneity in the utility of having an active opinion on the transition trajectory are investigated. This is done by giving the individuals a random uniform probability density function for the utility of having an active opinion. In figure 6, a bandwidth of 2 is chosen for the utility of having an active opinion. This experiment is done to replicate the effects Scheffer predicted by using the law of large numbers.

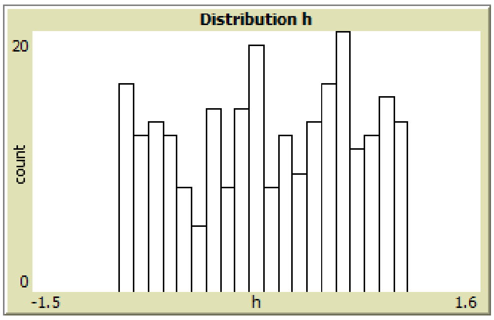

Figure 6 The distribution of the perceived severity of the problem of the agents when the bandwidth is two.

Leaders

Leaders are added who have more influence than other agents. There are 10 leaders, which have 5 times more influence than the other agents. There is still a mean-field approach used. So, there is no social network used. This experiment is done to see whether the effects of leaders are the same as Scheffer predicted. Scheffer did not model the leaders explicitly in a model.

Continuity in attitude

Instead of only active or passive an agent can also be neutral regarding the problem. It takes less cost to switch from a passive to a neutral opinion than from a passive to an active opinion. In this way, the effects on critical transitions can be investigated.

4.6 Results

Reproduction of the mean-field approach

This first experiment shows that the results of the critical transition model can be accurately reproduced. Figure 7 shows the results of the agent-based model and the analytically solution of Scheffer’s critical transition model. The agent-based model is less smooth because the agents decide their attitude based on a probability. In the models, we used 250 agents. Previous experiments showed that increasing the number of agents increased the smoothness of the graphs. This first experiment was repeated 10 times to create a confidence interval. The graph with high cost of deviation is different because the agent-based model does not show instable point. But the stable points are accurately reproduced. It is not a big problem that the instable points are not reproduced because in Scheffer’s theory they are also not used except in the figures.

When there is low cost of deviation in your attitude, the average public opinion is proportional to the perceived severity of the problem. However, when there is more cost of deviation there is initially inertia because it is hard to have a different opinion when everyone else has a passive attitude regarding a problem. After the inertia, there is positive feedback loop because when more people become active it becomes easier to also become active due to less cost of deviation from the average. When the cost of deviation is very high there is a lot of inertia and the attitude is not proportional to the perceived seriousness of the problem. After the inertia, a sudden shift happens in the average public attitude from passive to active. At this point the perceived severity of the problem is large enough to overcome the cost of deviation from the average. When a few people change, quickly everyone changes because the perceived severity is high and the cost of deviation becomes less.

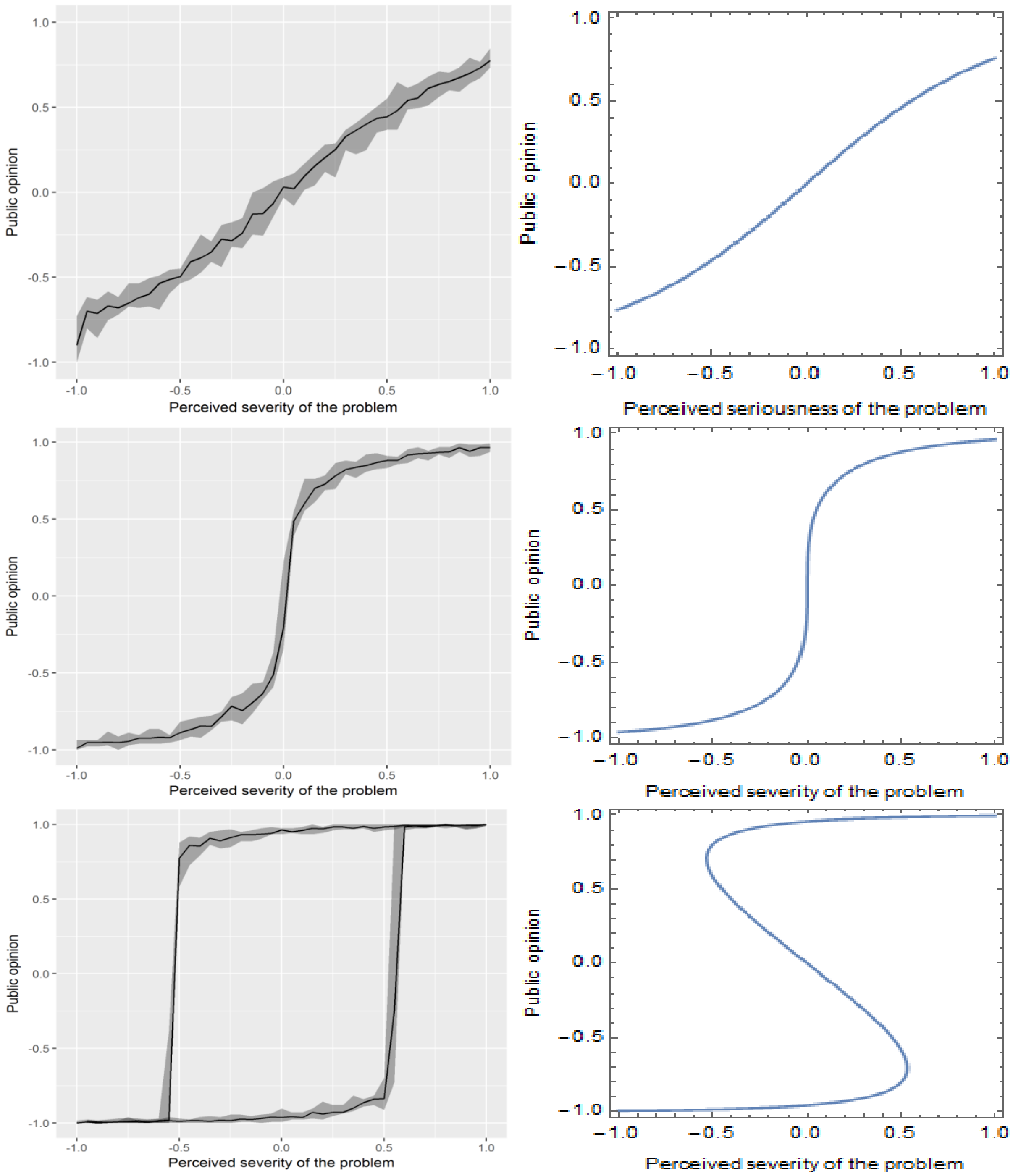

Figure 7 The original critical transition model (right) and the reproduction of it using ABM (left).

Peer pressure in lattice network

For the nearest neighbor experiment, the cost of deviation becomes less influential than in the mean-field approach. In the mean-field approach, the agents are influenced by the average attitude. However, in the nearest neighbors approach the agents are influenced by their 4 closest neighbors. In the mean-field approach, the agents who are active are homogenously spread because they don't care very much about what their neighbors do. However, when there is a social network, the agents decide based on their neighbors what their attitude is regarding a problem. At a high cost of deviation this causes the formation of clusters, because the agents want to do the same as their social network. It is easier for the agents to have an active attitude while the average has a passive attitude because the agents can surround themselves by other agents who also share the same attitude.

In appendix D1, can be seen that when the agents have more connections also more hysteresis occurs. And when the agents are connected with all other agents than the results are the same as the mean-field approach.

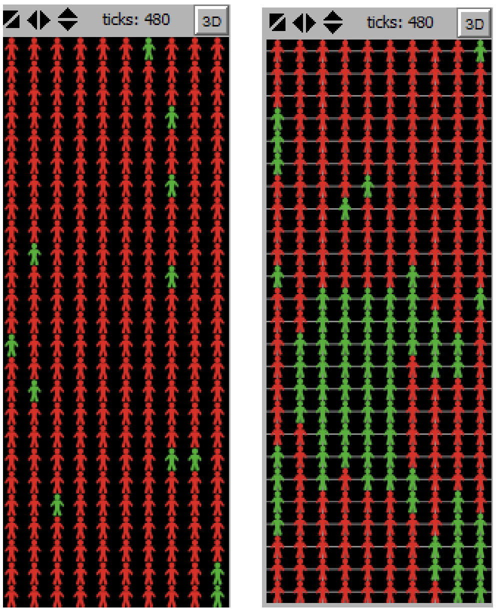

Figure 8 Mean-field experiment (left) and nearest neighbors experiment at the same perceived severity of the problem.

Heterogeneity in perceived severity of the problem

In case there is heterogeneity in the attitude of the agents there is less inertia in change in attitude. This is also what Scheffer predicted when the agents became more heterogeneous in attitude. In the other cases, all the agents are assumed to have the same perceived severity of the problem. When there is heterogeneity, all the agents have different perception of the severity of the problem. This causes that some agents perceive the problem very serious. These agents are likely to take early action, which leads the agents who perceive the problem also serious to follow. Until finally everyone acts. When the agents are all homogeneous in their perception of the problem, there are no agents who perceive the problem very severe. In this case there is no early attitudinal change. According to the model with heterogeneity it does not matter that there also agent who are don't perceive the problem serious, when there are a few who do perceive it very serious. Because the agents who perceive the problem very serious change their attitude anyway.

Appendix D2, shows that when the heterogeneity gets even larger less inertia occurs.

Leaders

The results of the model show that there is more inertia in attitudinal change when leaders are added. This is the opposite of what Scheffer predicted. Based on literature Scheffer predicts that when there are strong opinion leaders there is less inertia. These leaders are assumed to mobilize other agents because they are well connected, have high social capital, are early adopters by nature and can cause emotional contagion (Scheffer et al., 2003). In this model, the leaders are assumed to also use peer pressure for promoting vested interests.

The difference is that in this model the leaders can counteract and promote change, while in Scheffer’s model the leaders are assumed to only promote change. In this model, the leaders are assumed to have more peer pressure on the other agents. Initially the leaders are passive, by influencing the other agents, the other agents stay also passive until finally the perceived seriousness is large enough to overcome the peer pressure. Scheffer assumes that leaders only act to promote change. However, leaders may also influence others to stay in the status quo regarding a problem. They can do this by using the same social influences for promoting change.

In appendix D3, as more leaders are in the model, there is more inertia. When there are more leaders who counteract change, individuals are more influenced to stay in the status quo, and therefore there is more inertia.

Continuity in attitude

In the original model of Scheffer, the agents can have a positive or a negative attitude regarding a problem. In the new model, the agents can also have a neutral attitude regarding a problem. This causes the inertia due to the cost of deviation to be much less. Initially when the average public opinion is passive and the peer pressure is high it is hard to have a positive attitude regarding a problem. However, it is something easier to have a neutral opinion because then the agent does not have to deviate much from the average attitude. This causes much more initially change by agents who become neutral and then it becomes also easier for other agents to change their attitude. In figure 9, for the same perceived seriousness of the problem the agents have a more active attitude in case they have 3 possible attitudes instead of 2.

In Appendix D4, an experiment is shown where agents have five different attitudes regarding a problem. In that case the inertia due to cost of deviation is even less than with 3 different attitudes. So, when there is a problem where there is a continuous distribution of opinion less inertia is expected than when the attitudes are more binary.

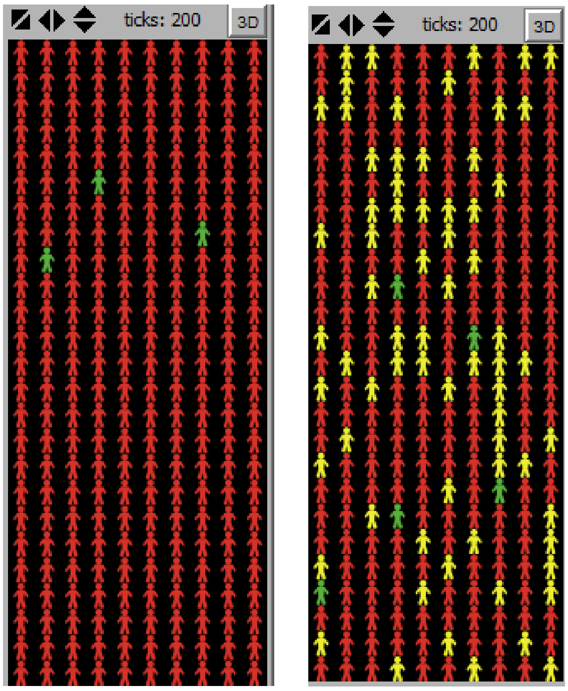

Figure 9 Individuals can only have an active or passive attitude (left) and individuals can have an active, neutral or passive attitude (right). Both experiments are the same perceived severity of the problem.

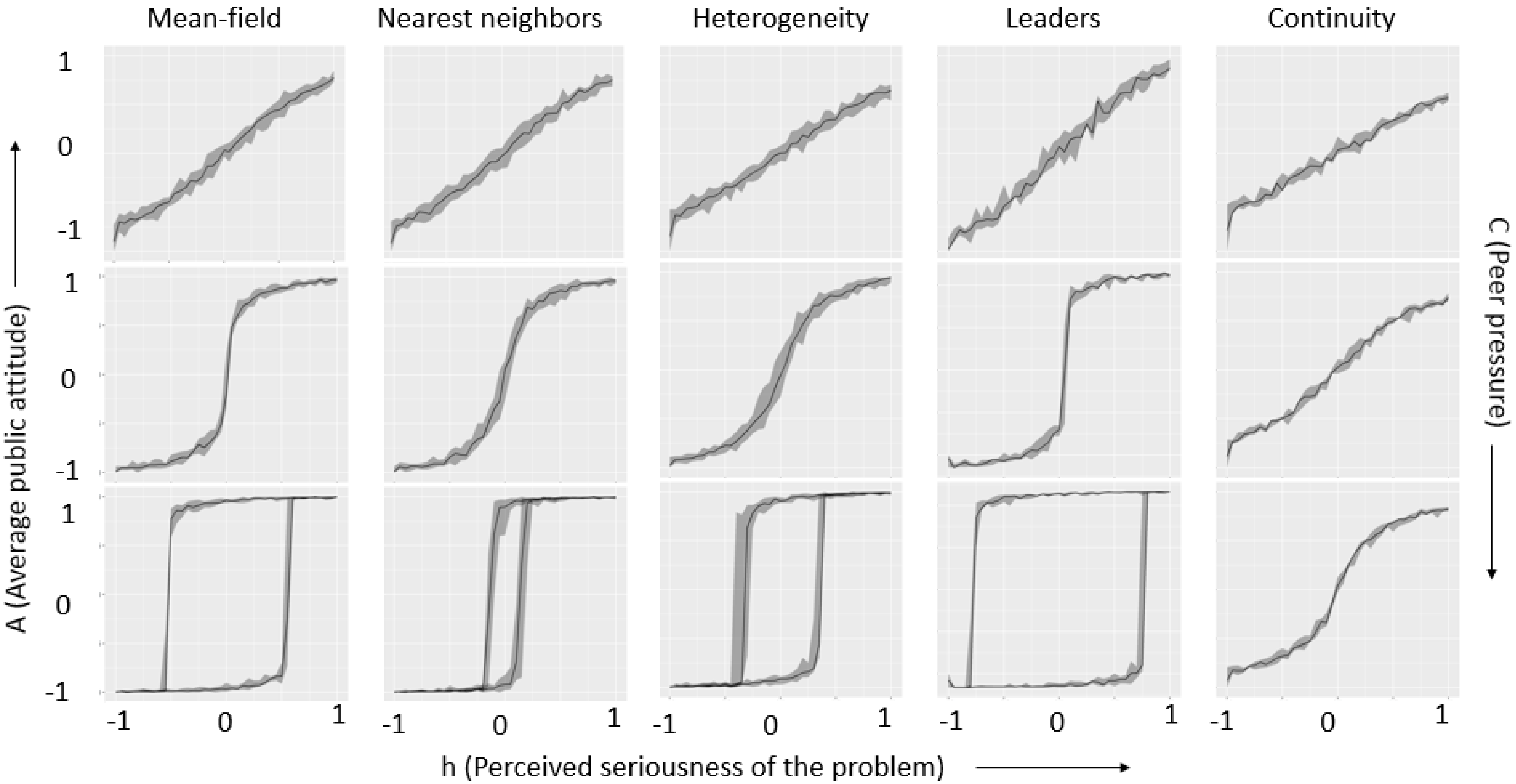

Figure 10 Results of the ACT model. On the left is the original model. The nearest neighbors, heterogeneity, leaders and continuity experiment are changed one parameter compared to the mean-field experiment.

Overview results

In table 3, an overview of the results of the ACT model compared to the model of Scheffer can be found.

Table 3 Overview of the results of the ACT model compared to the original model

	Scheffer	**ACT**	**Effect**
Model	Mathematical	Agent-based	Same results when reproduction
Network	Mean-field	Networks	Faster transition than Scheffer
Leaders	No leaders	Leaders	Leaders counteract change instead of promoting change
Heterogeneity in attitude	Law of large numbers	Explicitly modelling in ABM	Same effect as Scheffer
Attitude	Active or passive	Active, neutral or passive	Hysteresis disappears

Relationship with the energy transition

Scheffer’s critical transition model is a model about public opinion regarding a problem. This problem can be climate change. In this way, the model gives insight about public opinion regarding climate change. The agents can represent individuals or countries and their choice of attitude regarding climate change. The various models show the different attitudes of the agents due to different inputs in the model. In the discussion, the results will be related to the energy transition in more detail.

5. AGENT-BASED TRAGEDY OF THE COMMONS (ATOC) MODEL

5.1 Missing elements and adaptations Tragedy of the Commons model

There are a few elements missing in the existing ToC model and adapted for the AToC model. A summary of these changes can be found in table 4.

Table 4 Summary of missing elements ToC model and requirements.

Schindler	**Requirements**	**Energy transition**
No ecological value	Ecological value and heterogeneity in it	Countries care a different amount about climate change.
Complete information about the state of the grass	Perceived state of grass by herdsmen	Counties have different perceptions of the problem due to their climate and climate disasters.
Number of cows does not influence interest in keeping grass	Number of cows does influence interest in keeping grass	No relationship with energy transition.
Dominant disposition of herdsmen	Herdsmen acts on different dispositions	Countries act on multiple dispositions regarding climate change.

Ecological value

In the original MASTOC-s model, the herdsmen do not have an ecological value. They are assumed to only act on short-term profit. However, in the energy transition countries care about the climate outside of short-term profit.

Therefore, in the new model a heterogeneous ecological value is introduced. A herdsman with a high ecological value represents a country who cares a lot about climate change. While a herdsman with a low ecological value represents a country, who does not care much about climate change.

Incomplete information

In the original model, the herdsmen have perfect information about the state of the grass. However, regarding climate change there is incomplete knowledge about the state of the climate and the effect of climate change is different depending on the place.

Therefore, in the AToC model herdsmen perceive the state of the grass based on the grass in their surroundings.

Interest in keeping grass dependent on number of cows

In the MASTOC-s model the herdsmen do not consider their number of cows when deciding about adding or removing a cow. However, it can be argued that when a herdsman has a lot of cows it has more interest in keeping the grass. While a herdsman with a small number of cows has less to lose and therefore can add more easily cows.

In the AToC model, the herdsmen consider their number of cows. However, it can be argued that in the energy transition a country with a large amount of emissions has not more interest in keeping the climate sustainable than a country with less emissions.

Herdsmen behavior dependent on multiple dispositions
In the original model, when the agents consist of two dispositions and the level of selfishness is higher than the level of conformity, it will act selfishness all the time. However, in reality individuals act sometimes selfish and sometimes due to conformity.

Therefore, in the new model a herdsman can act sometimes selfish and sometimes on conformity.

5.2 Conceptualization

The model consists of herdsmen, cows and grass, as can be seen in figure 11. They are placed on a 33 x 33 grid. There are 10 herdsmen with a physical location on the grid and each of them has their own cows. The herdsmen each have a level of environmentalism. Besides that, they have levels of the dispositions selfishness and conformity. The cows have a physical location on the grid. There are 1089 land patches and they can be in a grass or non-grass state.

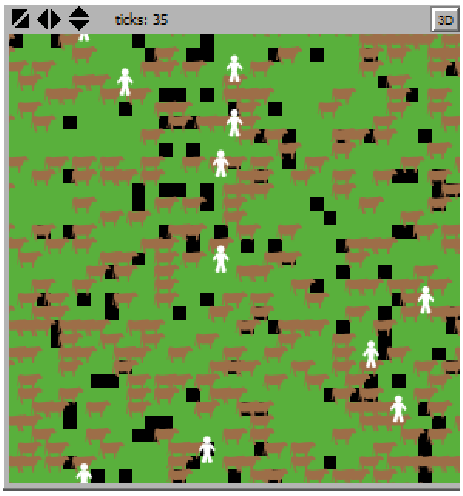

Figure 11 The Tragedy of the Commons model in Netlogo, consisting of herdsmen, cows and grass.

5.3 Narrative

The complete model description and Netlogo implementation can be found in appendix E.

Initialization

Initially, 10 herdsmen are created. Every land patch is grass and 0 cows are created. The cows and herdsmen get a random position on the grid. The herdsmen are initialized to have a certain level of selfishness, conformity and an ecological value, which represents how much they value the grass outside of financial reasons.

Experiment runs

After the initialization, the following cycle is repeated:

1. Cows grazing
2. Grass regrowth
3. Herdsmen decide to add or remove 1 cow

When the cows graze, they walk to the grass patch closest to them and eat it. The grass patch turns into a non-grass patch. When there is not enough grass for a cow, it dies.

After that there is grass regrowth, which depends on the grass regrowth function. The grass does regrow depending on how much grass there currently is and the new grass is placed at random locations.

Then, the herdsmen decide to add or remove one cow to their livestock. They do this based on their dispositions, the perceived amount of grass available, and their interest in keeping the grass, which is based on their number of cows. When the total reward for adding a cow is larger than 0 the herdsman is more likely to repeat that behavior. This is the same for removing a cow. This is explained in more detail in paragraph 5.4.

5.4 Differences with the MASTOC-s model

Grass growth curve

The MASTOC-s model uses a logistic growth function, as can be seen in equation 8.

$$Veg_{t+1} = Veg_t + rate * Veg_t^2 * \left(1 - \frac{Veg_t}{Veg_{max}}\right) \quad (8)$$

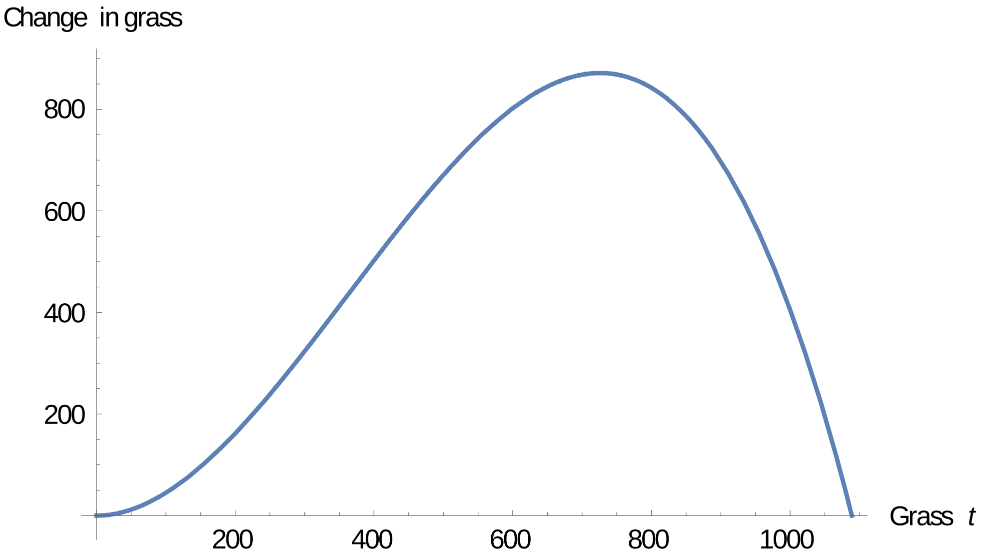

Figure 12 The change in grass in the original model.

The new model uses an adapted logistic growth function:

$$Veg_{t+1} = Veg_t + \frac{Veg_{max} - Veg_t}{1 + Exp[-0.008 * (Veg - 545)]} \quad (9)$$

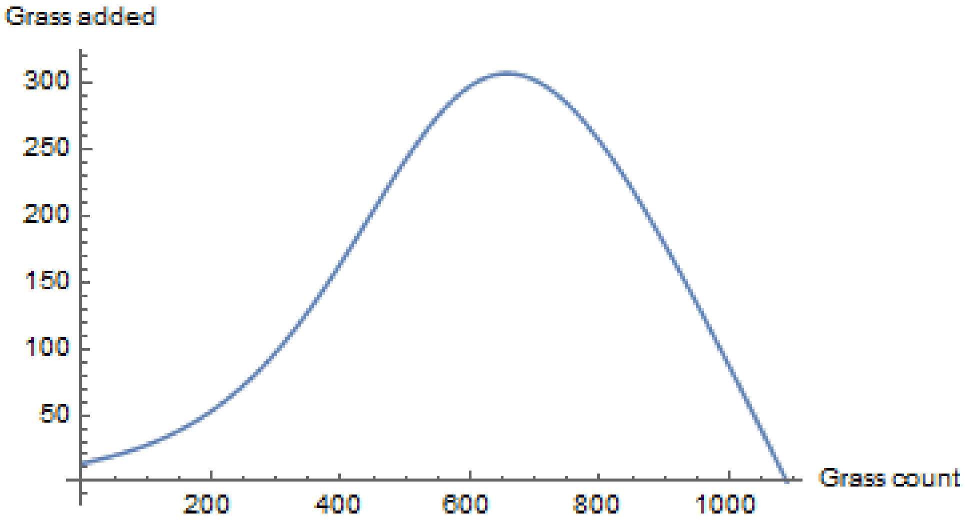

Figure 13 The change in grass in the newly created ABM. Now, there is grass growth when all the grass is gone.

The grass growth functions have the same form but the difference is that the new growth curve gives the possibility to regrow grass, when there is no grass left.

Benefit function of a selfish disposition

In the original model, the benefit function of a selfish disposition is:

$$benefit_{self} = x_i * P_{cow} - \frac{cost\left(K+\sum_{j\neq i} x_j, K+\sum_j x_j\right)}{\#herdsmen} \tag{10}$$

The benefit of a selfish herdsman, is assumed to be the profit of an extra cow minus the lost pasture potential caused by the extra cow divided over all the herdsmen. With this equation, the reward for the previous action taken is calculated. x_i is the previous action of herdsman *i* and can be -1 or +1, removing or adding a cow. The cost function is the change in pasture potential due to the last action of the herdsman. *K* is the total number of cows. The loss of pasture potential is calculated by this equation:

$$cost(x, y) = [g(\max(0, Veg - x * Requ)) - g(\max(0, Veg - y * Requ))] * \frac{P}{Requ} \tag{11}$$

In this equation, *x* and *y* are the previous and current number of cows. The function *g* represents the grass growth function and *Requ* the forage requirement of one cow. So, the loss of pasture potential is calculated by the new grass with *x* cows minus the new grass with *y* cows, multiplied by the profit per grass field.

In the new model, the benefit of a selfish herdsman is:

$$b_{self,i} = x_i - \Delta grass * [\frac{k_i}{f_{req} * K} + v_{eco,i}] \tag{12}$$

In this case $b_{self,i}$ is the benefit of a selfish herdsman *i*. x_i is again the last action by herdsman *i*, so +1 or -1. $\Delta grass$ is the change in grass after cow grazing and grass regrowth caused by the last action of herdsman *i*. k_i and K are the number of cows of herdsman *i* and the total number of cows. f_{req} is the forage requirement of one cow and $v_{eco,i}$ is the ecological value of herdsman *i*, which is how much the herdsman cares about the grass outside of short-term economical profits.

There are a few differences compared with the original equation. First, P_{cow} is left out of the equation because it didn't change the behavior of the herdsman and profit can also be expressed in number of cows instead of euros. Second, instead of dividing by the number of herdsman the change grass is now multiplied by $\frac{k_i}{K}$. In this way, herdsman with more cows value the grass more because they have more concern in keeping the grass. Third, an ecological value is added to create heterogeneity between the concern of the herdsmen about the grass.

In figure 14, the change in grass function is shown, which is in the previous equation. This function is positive when the herdsmen reduce cows and negative when the herdsmen increase cows. When there is a lot of grass available compared to the cows, the action of the herdsman does not matter because the action does not change the grass potential. However, when there are about 500 patches of grass after grazing then the action of the herdsman can influence the grass potential much more. Therefore, the herdsmen are more likely to reduce cows. In case, the grass after grazing becomes less, the herdsmen have less influence about it and therefore are a little bit more likely to add cows.

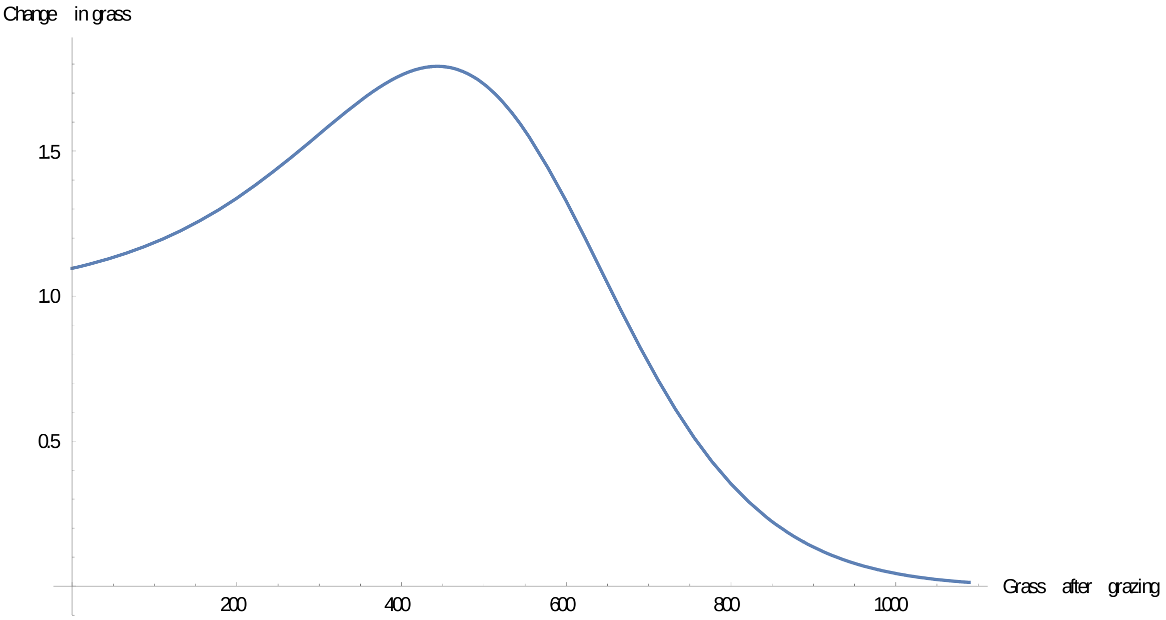

Figure 14 The change in grass caused by removing one cow. The change in grass by adding one cow is the opposite.

Addition of rewards of dispositions

In the original model, the rewards are added to each other. It applies that:

$$Total\ reward = \sum_i r_i * l_i \tag{13}$$

$$r_i = 1 \lor r_i = -1 \tag{14}$$

$$\sum_i l_i = 1 \tag{15}$$

In equation 13 is r_i the reward for the disposition *i* and l_i is the level of disposition *i* of the concerning herdsman. Equation 16 shows the reward calculated in the new model.

$$Total\ reward = \begin{cases} r_{selfish} & l_{selfish}\ \%\ of\ the\ cases \\ r_{conformity} & l_{conformity}\ \%\ of\ the\ cases \end{cases} \tag{16}$$

In this way, it is possible that both disposition influence the action of the herdsman instead of that one disposition is dominant.

Perception of the grass

In Schindler’s model, the individuals have perfect information of the amount of grass. However, in the new model the model can be extended with incomplete information of the grass. In case there is incomplete information, the perceived grass for each herdsman is calculated by extrapolating the grass in a certain radius of the herdsman. This formula is used for each herdsman:

$$Perceived\ grass = grass_{in\ radius} * \frac{total\ land}{land_{in\ radius}} \qquad \textbf{(17)}$$

This is done, to investigate the effects of different perspectives of the problem.

5.5 Experimental setup

The parameter settings in Netlogo of each experiment can be found in the appendix F. The other experiments are each adaptations of the fast adaptation experiment.

Fast adaptation

In this experiment, the herdsmen are completely selfish and they act directly on their rewards. Besides, they complete information about the grass field and have a homogenous ecological value. This experiment is done to have a base case towards which the other models can be compared and to look at the behavior of the herdsman.

Slow adaptation

Now, the herdsmen adapt slowly to their rewards. So, although it may be beneficial for a herdsman to remove a cow, it takes time for the herdsman to adapt due to habit and limited cognitive resources. In this way, we can learn about the effects of these human behaviors.

Perception grass

The herdsmen their perception of the problem is based on the grass around the herdsman instead of that they have perfect knowledge. This experiment is done to gain more insight in the effects of imperfect knowledge and different perceptions of the problem.

Heterogeneity of the ecological value of the herdsmen

The herdsmen now have a heterogeneous ecological value which is assumed to be random distributed across the mean ecological value. Heterogeneity in ecological value applies to the Tragedy of the Commons as well as the energy transition.

Conformity

In this experiment, the herdsmen have conformity towards what the other herdsmen do. When most of the other herdsmen did add a cow in the last time step, the herdsman is more likely to do the same. The same for reducing a cow. This is experiment is done because of the human nature to imitate others.

5.6 Results

Fast adaptation

At the fast adaptation experiment, all the herdsmen act the same. When the herdsmen have a low ecological value, they add cows until finally a collapse happens because all the grass is grazed by the cows and the cows die. The herdsmen are assumed to be shortsighted and the grass does not have a chance to regrow because the herdsmen stay adding cows. At a somewhat higher ecological value there is no collapse because the herdsmen value the grass more. When the ecological value of the herdsmen is even higher the herdsmen decide not to add any cows anymore at a lower number of cows.

Slow adaptation

When there is slow adaption of the herdsmen, there is an overshoot in the number of cows compared to the fast adaptation experiment. The herdsmen take longer to adapt and this causes that they stay increasing their cows, which now also causes a collapse in the middle row of figure 15. At a high ecological value, the herdsmen first have an overshoot because they need time to adapt. After the overshoot, they have an undershoot because now they need time to adjust from reducing cows to adding cows. In this way, the number of cows oscillates around the number of cows in the fast adaptation experiment.
The number of cows per herdsman differ now from each other because the slow adaptation is a stochastic process. The herdsmen do now have a probability that they add or remove a cow.

Perception grass

The agents do have different perceptions of the state of the grass and therefore now act differently. The herdsmen are assumed to have incomplete information. At a low ecological value, they don’t care much about the grass and therefore a collapse follows. At a medium ecological value, whether a collapse happens depends on the perception of the herdsmen of the problem. The grass amount is around a tipping point for collapse. When a few herdsmen perceive the problem not to be big because they have a lot of grass around them, they stay adding cows. This will lead to a collapse. The grass does regrow on random location. The herdsmen look at the grass close to them for their perception of the problem. The grass regrowth is a random process and therefore the herdsmen perception is too. Therefore, the collapse can happen at different times because the herdsmen act depending on their perception of the problem. The grass does also grow back from a collapse depending on the perceived severity of the problem by the herdsmen. When the herdsmen think there is no grass left anymore they do not add cows anymore. At a high ecological value, there is no collapse but there is stochasticity due to the different perception of the problem.

Heterogeneity of the ecological value of the herdsmen

At a low ecological value, there still follows collapse. However, figure 16 shows that some herdsman with a high ecological value try to reduce their cows after a while. When the ecological value is higher, the herdsmen try to reduce their cows earlier. Due to the heterogeneity, there are differences between the number of cows per herdsman, as can be seen in figure 16. The herdsmen with a high ecological value try to reduce their cows earlier.

There is a zig zag pattern in the middle row of the cows per herdsman graph. The herdsmen first decrease their cows because they perceive the amount of grass after grazing to be little. When the grass is little, the herdsmen value the grass more because adding or removing a cow has then more effect on the grass potential. After reducing cows, the grass has time to regrow and then the herdsmen start adding cows again. And this is iterated a few times. Each time the herdsmen with a low ecological value start adding cows earlier.

At the low ecological value, there is one run of the total number of cows where it takes a long time for a collapse happens. This can be explained by the chance process of the ecological values. The ecological values are randomly chosen for each herdsman between a certain bandwidth. By chance the ecological values of that run are relatively high. In appendix G1, the ecological values and the cows per herdsman are shown of this special case and a normal other run, to show proof of this explanation.

The cows per herdsman graph, shows an equilibrium of the cows at the end. This is caused by that herdsmen with a low ecological value have more cows. They have more interest in keeping the grass field because they have more cows. This cancels each other out, which causes them to stay at an equilibrium number of cows.

When the heterogeneity in the ecological level gets larger it is more likely that a collapse follows, as can be seen in appendix G2. This is caused because there could be an outlier who does not care at all about the grass field. This herdsman, keeps adding cows regardless of the state of the grass field. Even having more interest in keeping the grass field because of his numbers of cows does not withhold this herdsman from adding cows.

Conformity

At a low ecological value, there is in all cases a collapse. At the medium ecological value, the total amount of cows rises and then oscillates around the 300 cows. When other herdsmen add cows, a is tempted to also add a cow. This is similar for reducing cows. In this way, it is still possible to get a collapse when the herdsmen influence other to also add cows. When the herdsmen act due to peer pressure is a stochastic process. Therefore, the moment of collapse differs per iteration of the experiment. At a high ecological value, the number of cows oscillates but never goes past a tipping point for collapse.

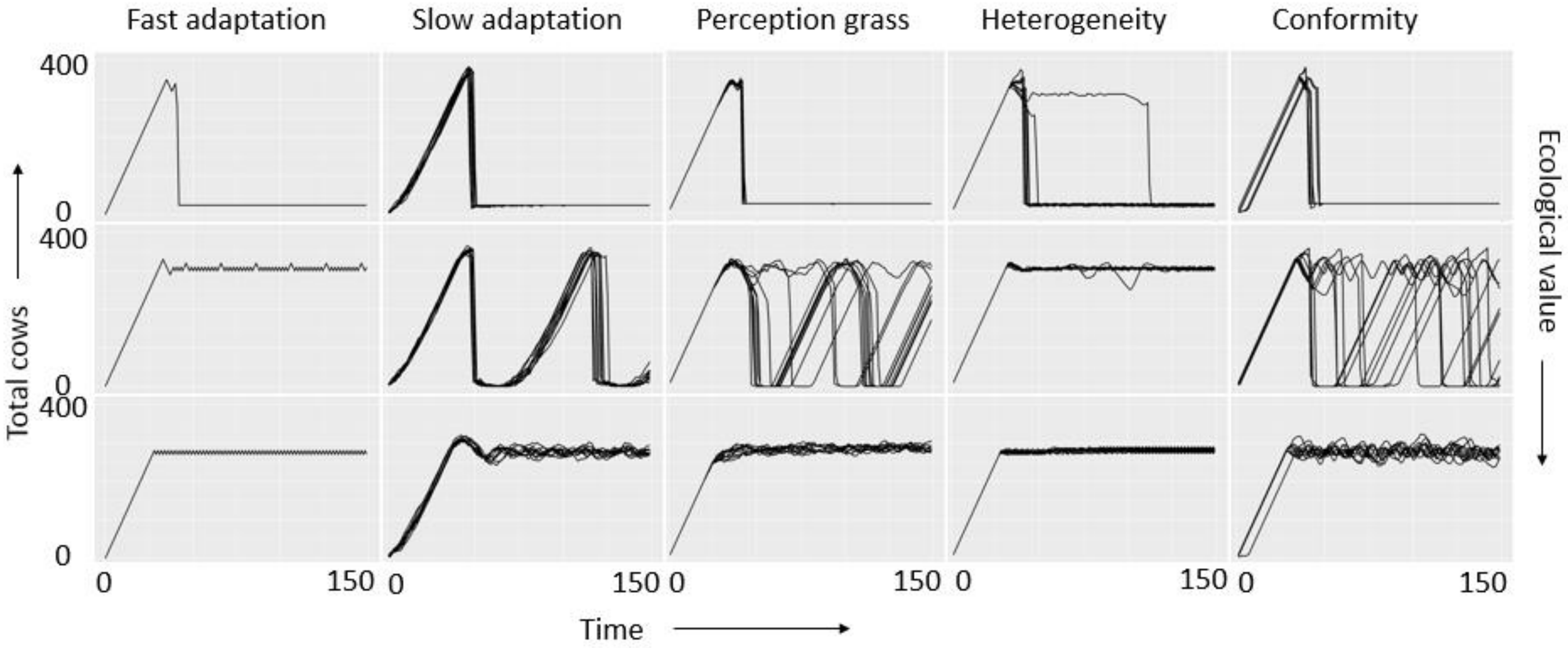

Figure 15 Results of the Tragedy of the Commons model. Ten repetitions of each experiment are shown. The total cows of the herdsmen are shown over time. On the highest row, is the ecological value low. On the lowest row, the ecological value is high. The other experiment are one parameter changes compared to the fast adaptation experiment.

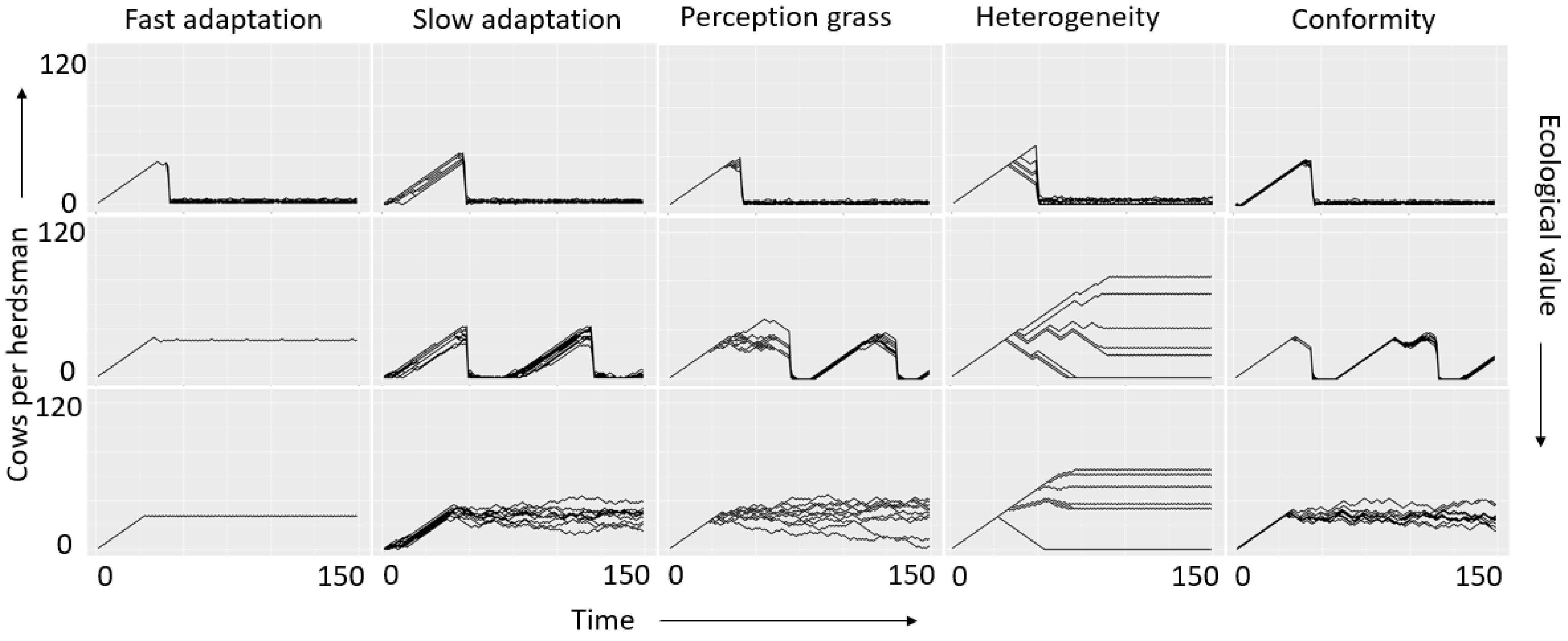

Figure 16 Results of the Tragedy of the Commons model. One repetition of each experiment is shown. The graphs display the cows of the ten different herdsmen over time.

Overview results

In table 5, an overview of the results of the AToC model can be seen.

Table 5 Overview of the results of the AToC model

AToC	**Effect**
Slow adaptation	Tragedy more likely
Incomplete information	Heterogeneity in behavior of herdsmen
Heterogeneity ecological value	Heterogeneity in behavior of herdsmen
Conformity	Tragedy more likely

Relationship with the energy transition

In the AToC model the common pool resource is the grass. While regarding the energy transition the common pool resource is the carbon budget. In the discussion, the link between the results of the AToC model and the energy transition will be further discussed.

6. DISCUSSION

The energy transition is much more complex than these two simple models. However, we could still learn something about the dynamics of the energy transition. Therefore, the models must be a close enough representation of reality to gain some insight of it, without becoming too complex. In the next two paragraphs, interpretations between the results of the two models and the energy transition is given. Besides, there is discussed whether the ACT and AToC models and its interpretation are representative enough of reality to be useful. The experiments done in both models will be discussed one by one on this.

6.1 ACT model

Reproduction results Scheffer

The first experiment was a reproduction of the results of Scheffer. The results were accurately reproduced and this serves as an extra validation of the correct implementation of the ACT model. In the critical transition model of Scheffer the cost of deviation towards the average public attitude is caused by peer pressure. However, it can be argued that more factors cause this cost of deviation. There are many forms of other influences, which cause a cost of deviation. For example, social norms, vested interests, information spread, habits and contagion in behavior. Another cause of cost of deviation is that a product may become more valuable when there are more users of it. For example, when there are more electric car charging stations, the value of electric cars increases.

The ACT model shows that critical transitions happen at a high cost of deviation. In the ecology theory were this model is based on, there is an instant change from one stable state to another. For example, a turbid lake turns instantly into a clear lake when a certain tipping point is reached. However, in society critical transitions of public opinion regarding a problem do not happen instantly. Still, it is argued that this model can be useful because the model shows information about inertia and the pace of the transition. A critical transition must be seen as a rapid change, not an instant change like transitions in the ecology field.

Some other important elements are left out the model. For example, the cost and quality of sustainable technology. Although, this is an important factor for the pace of the energy transition. The cost of deviation, is argued to still be a valuable building block for a narrative regarding the energy transition because humans often act based on short-term drives and not fully rational.

Social network

In the next experiment, a social network was introduced to the critical transition model. It is argued that in many cases humans are influenced by their peers in their social network and not by the average public attitude. For example, when someone lives in a neighborhood with a lot of solar panels, that person is more likely to adopt also solar panels. He is less influenced by the average number of solar panels in his country. In the ACT model, there is a nearest neighbor network used. The agents are influenced by other agents close to him in his network. However, in the mean-field approach used by Scheffer the agent is assumed to be influenced by the average of all agents.

This implies that inertia in public opinion is less likely because in societies with high peer pressure there arise early clusters of like-minded people instead of everyone changing at the same time.

For this experiment, a nearest-neighbor network was used. The agent was influenced by the average attitude of his four closest agents. This is a simplification of the social network and influences. However, it is still more representative in some cases than influence by the average attitude of all agents.

Besides, it must be noted that there are many influences on an agent his decision making. The effect of his peers is only a small one.

Heterogeneity in attitude

In the next experiment, the effects of heterogeneity in attitude regarding a problem were investigated. Scheffer used the law of large numbers. However, in the ACT model the perceived severity of the problem was randomly divided among the agents. The results of the original model were again similar as the ACT model. This gives another validation of the model.

The results can be connected to the energy transition. Regarding climate change the opinions about the severity of the problem of individuals are widespread. Because of this the results of the ACT model predict that in societies with a high cost of deviation the probability is small that there occurs inertia and then a sudden shift in public attitude regarding climate change.

To put this results in perspective, it can be argued that heterogeneity contributes as well counteracts early change. On the one side, heterogeneity causes outliers such as Trump to counteract change. On the other side, there are positive outliers, which take early action regarding climate change. In case there is high cost of deviation and the average public attitude is passive heterogeneity in opinion promotes change because then some people take early action. When these people take early action, others may join. However, in case there is already some action taken, high heterogeneity in public attitude may counteract as well contribute to change.

So, the effect of heterogeneity depends on the circumstances and does not necessary have to contribute or counteract change. Scheffer predicted heterogeneity in attitude to contribute cause. This is elaborated to be only in case when there is no action taken and there is high peer pressure. In other cases, it is disputable.

Leaders

The results of the model showed, that leaders in the model cause inertia and then a sudden shift. However, it was predicted that leaders accelerate change. A possible explanation of this is that there are two types of leaders. The first one, are leaders who take the initiative for change and influence others to join. The second one, are vested interest of the current technology. Regarding climate change, leaders can be countries with high renewable energy sources like Norway, Sweden and Switzerland. These countries help other countries in becoming more sustainable by providing technology, a success example and the peer pressure to also become sustainable. However, leaders regarding climate change can also be assumed to be companies or countries, which are reliant on keeping fossil fuels to maximize their profit. This type of leaders causes inertia and sudden shift regarding climate change action.

Addition neutral attitude

The last experiment showed, that with the addition of a neutral attitude that there was no hysteresis anymore. This was caused because there was less cost of deviation to switch from passive to neutral than from passive to active. A possible explanation of this is that when there is the possibility of taking small steps less inertia occurs. This is because people than must change less and they feel less resistance. It is then easier to change habits, less resistance of vested interests and less social influences due to peer pressure or social norms, which causes the cost of deviation to be less. For example, a small step can be to install solar panels on your home. While a big step would be to live fully on renewable energy. In America, there must be voted between the Democrats or Republicans, they have a very different climate policy. Therefore, there must be chosen between big deviation, which causes inertia or sudden shifts in climate policy. In the Netherlands, there is more the possibility of small steps because the government acts on consensus. There does not have to be chosen between two wide ranging parties but there is also middle ground possible.

The addition of a neutral attitude with less cost of deviation showed that in case there are small steps possible, more early action is taken.

Regarding the energy transition, there are almost always small steps possible. However, there are some decisions were large deviations are taken. These cause inertia or a sudden shift. For example, the Paris agreement and the election of Trump are large deviations.

Overview relation results ACT and the energy transition

In figure 17, an overview of the effects investigated by the ACT model can be found. The original figure of Scheffer can be found in paragraph 2.2.

When there is a low cost of deviation early action is taken. However, when there is a high cost of deviation there is inertia because of actors like peer pressure, contagion in opinion, information bubbles, social norms, habit, vested interest or value increase of large used products.

When an individual is influenced by the average public attitude, there is more initial inertia. However, in case the individual is influenced by his peers in his social network. There is more early action taken because at a high cost of deviation individuals can form bubbles where they take together with their peers an active public attitude.

The new theory proposes that vested interest cause inertia until the severity of the problem reaches it tipping point. Then, society finds the effects of climate change are very severe and a sudden shift in opinion happens. According to this theory leaders take early action, which causes other people to join these early leaders.

Lastly, the possibility of small steps instead of large deviations causes the transition to be smooth. When there must be large deviations taken there could be inertia or a relatively sudden shift.

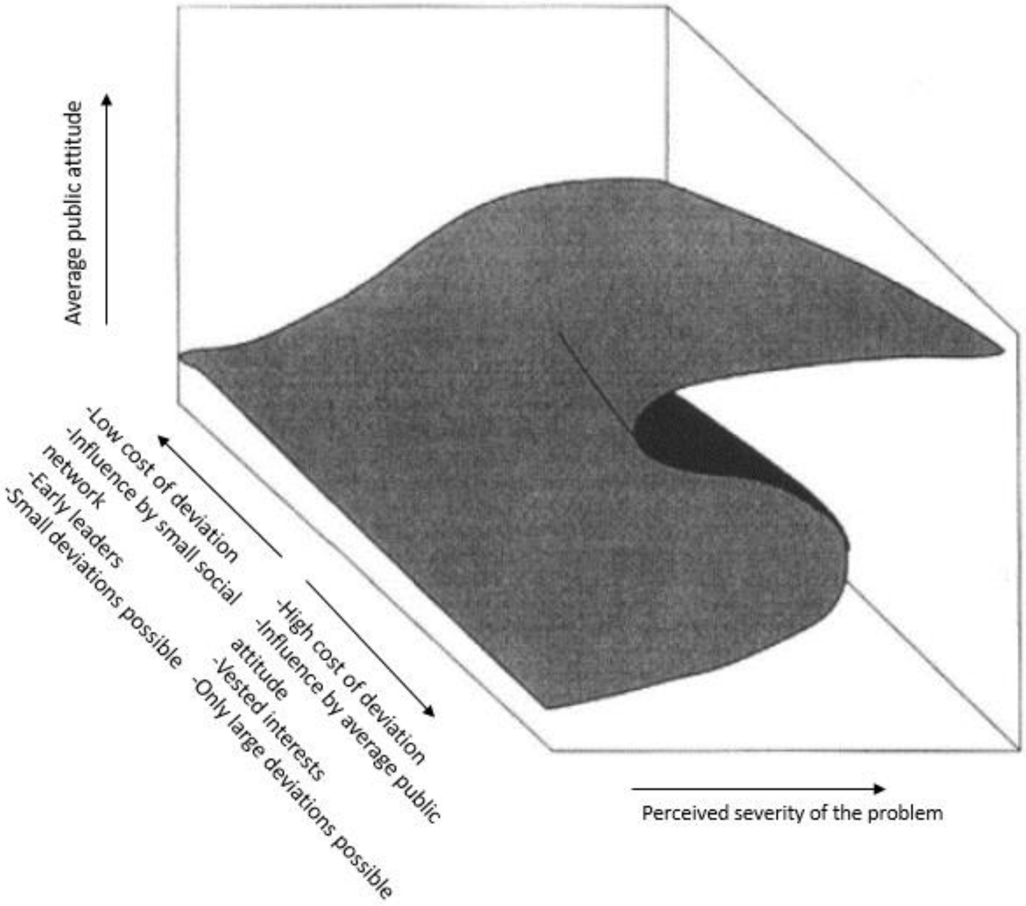

Figure 17 Overview of the effects investigated by the ACT model on the transition trajectory of the average public attitude.

6.2 AToC model

The Tragedy of the Commons model does have some overlap with the climate change problem. In both cases there is a common pool resource. In the model of Schindler, the common pool resource is the grass field and regarding climate change it is the carbon budget. The cows of the herdsmen can represent the CO2 emissions of countries. One difference is the grass growth function. While grass can regrow on a pasture, the carbon budget is hard to restore. Possible ways to do this are with direct air capture and carbon capture and storage. The ecological value represents how much people care about the climate. In the real world, this differs per country.

Slow adaptation
The slow adaption experiments showed that when the herdsmen take some time to adapt that they are more likely to overgraze the grass. In the AToC model the herdsmen still added cows even though the grass field was almost depleted. Although the herdsmen in the AToC model wanted to change after a certain moment, they still took some time before making the action they wanted.

Regarding the energy transition it shows that society may be slow to adapt to rising carbon levels which causes severe levels of climate change to occur. This slowness of response may be caused by the finite human capacity to adapt.

Perception of the problem

The results of the AToC model showed that different perceptions of the problem caused herdsmen to have a different number of cows.

This can be related to the energy transition. Different perceptions of the problem can occur due to different effects of climate change in different countries. For example, a country which does have trouble with the climate may perceive the problem more severe than a country where they do not have trouble with it. Besides, different perception may occur due to climate disasters. For example, when a flood happens there is more concern over climate change and there is a greater willingness to act on energy savings (Spence, Poortinga, Butler, & Pidgeon, 2011). In the same way as the AToC model, countries that perceive the problem to be bigger due to their climate or climate disasters may act more on having less carbon emissions than other countries.

Heterogeneity environmentalism

The AToC model showed that different levels of environmentalism caused the herdsmen to have different number of cows. However, herdsmen with more cows did have more interest in keeping the grass than herdsmen with a little number of cows. Therefore, they were more likely to remove cows. The higher the heterogeneity gets, the more it contributed to a Tragedy of the Common in the AToC model, as can be seen in appendix G2.

However, this data may not be representative for the energy transition. In the AToC model, a herdsman could not reduce his cows below 0. Therefore, it was harder to reduce the total number of cows of all herdsmen. Someone herdsmen did have 0 cows and were willing to reduce this further but could not do this.

Regarding the energy transition there is almost always room for reducing emissions of a country. When a country already has 0 emissions it can even have negative emissions or help other countries in reducing their emissions. Therefore, it is unsure whether the results of the AToC model are valid for the energy transition.

Heterogeneity in environmentalism causes there to be positive outliers and negative outliers it is dependent on the situation whether the positive outliers offset the negative outliers.

An analogy can be made between the different number of cows and the different amount of emissions a country has. Countries who care a lot about the climate do have less emissions than countries who do care less.

Conformity

The results of the last experiment of the AToC model showed that conformity contributed to a Tragedy of the Commons. Conformity caused the herdsmen to act the same as the average of the other herdsmen. Conformity in the original model is the peer pressure of the other herdsmen.

However, regarding the energy transition countries do only slightly act on peer pressure of other countries. For example, the behavior of the country the Netherlands is caused by much more than only peer pressure of another country. However, the conformity modelled in the AToC model can be interpreted as the cost of deviation from the average. The cost of deviation is then caused by vested interests, limited cognitive resources, imitation and habit. These factors all cause it to be difficult to deviate from the average action of society.

Peer pressure itself can work as a catalyzer as well counteract change. For example, countries may feel peer pressure to follow up on the Paris agreement. However, at the same time people may feel peer pressure to act as other people and do not act on climate change. It is assumed that peer pressure causes society to more act like the average although this a rough assumption.

There can be found some literature on imitation by humans. For example, Festinger (1954) hypothesizes that when humans are unsure about their decision they tend to look to what other humans do. This implies that when a human is unsure about responding to climate change it looks around and sees what other people do. The level of action is low and because humans are socially influenced this reinforces the low level of action.

Overview relation results AToC and the energy transition

In figure 18, an overview of the results of the AToC model related to the energy transition can be seen. There are four possible outcomes regarding the energy transition: together sustainable, divided sustainable, Tragedy of the Commons or Tragedy of the Commons with free-riders.

Several factors make certain outcomes more likely. When there is a high perceived severity of the problem by countries, it is more likely that there will be a sustainable outcome of the energy transition. However, the human tendency of slow adaptation and the effects of a high cost of deviation cause a tragedy regarding climate change to be more likely. The high cost of deviation is due to peer pressure, vested interests, habit, the tendency to imitate of humans in unsure situations and limited cognitive resources of humans. In case of high heterogeneity in environmentalism or the perception of the problem countries will act divided. While one country may reduce emissions, another country continues emitting the same amount of emissions.

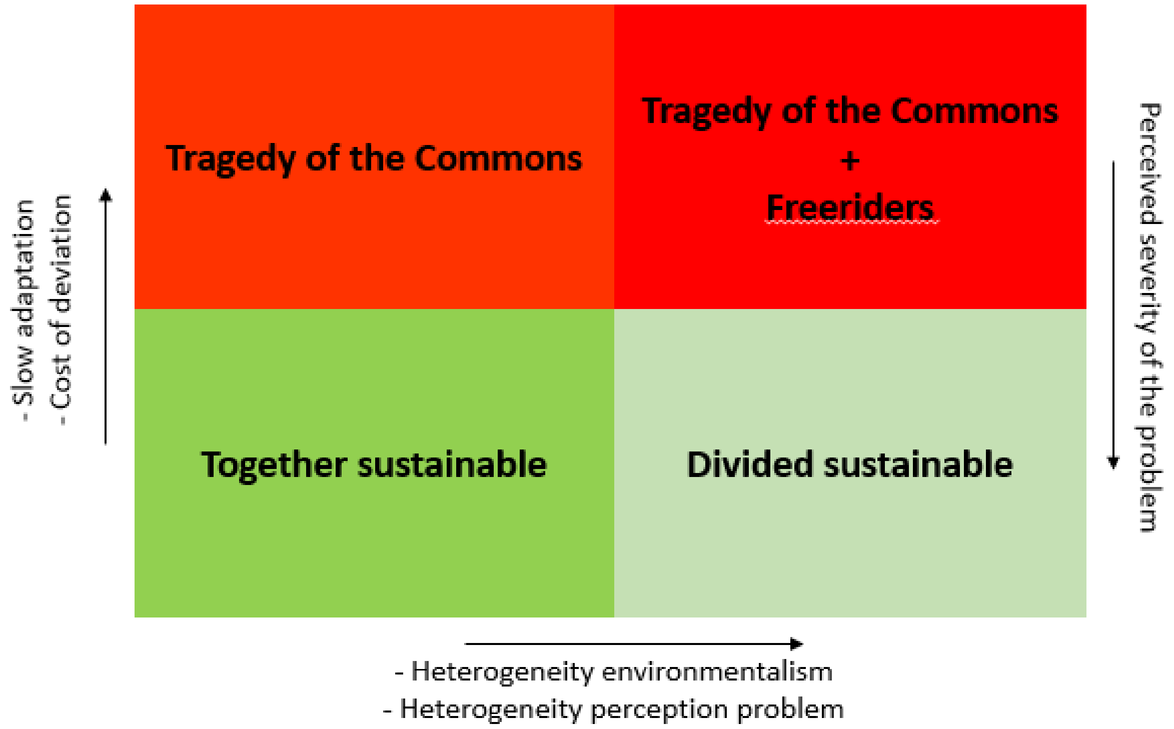

Figure 18 Overview of the possible outcomes of the energy transition and the causes of it based on the AToC model.

6.3 Comparison results ACT, AToC and the energy transition

An overview of the commonalities and differences between the two models and the reality of climate change action can be seen in table 6. The ACT model has a general problem while the in the ToC the problem is the loss of the grass. In the ACT model, the average public attitude represents the outcome while in the AToC model this is the total number of cows. Both models tested the effects of peer pressure and heterogeneity in opinion on the average attitude regarding the problem.

The grass in the ToC is the common pool resource. In the energy transition, the common pool resource is the carbon budget to stay below a certain impact of climate change. The cows in the ToC who graze the grass represent the carbon emissions. In the ToC the grass does grow back after it is grazed by the cows. This is an analogy with that technologies such as BECCS and DAC cause the carbon budget to grow back.

In the ACT model, as well in the AToC model conformity caused less action regarding the problem. In the ACT model, the conformity caused the individuals to stay passive because of the high cost of deviation. In the AToC the conformity was assumed to be caused by the psychological disposition of peer pressure. These effects of conformity on the energy transition are given an extra validation because both models show the same effects. In the AToC model, conformity caused there to be more cows grazing. While, in the ACT model conformity caused the average public attitude to be relatively passive.

Another overlap in experiment is the effects of heterogeneity in the perceived severity of the problem in the ACT model and heterogeneity in the ecological value of the herdsmen in the AToC model. It can be argued that these are relatively the same. The perceived severity of the problem as well the ecological value say something about how much an individual cares about the problem. Here the results of the two models are different. In the ACT model heterogeneity causes there to be early action taken. However, in the AToC model heterogeneity causes there to be free-riders who add cows while other herdsmen reduce cows. In the AToC model, in case there is heterogeneity of the ecological value it is more likely that all the grass disappears due to overgrazing. In the ACT model, heterogeneity causes there to be early individuals with an active attitude. While in the AToC model it causes there to be herdsmen who cause a collapse. This shows that the effect of heterogeneity is dependent on the circumstances.

Table 6: Overview of the overlap between the two models and the energy transition

Critical transition theory	**Tragedy of the Commons**	**Energy Transition**
Average public attitude	Total cows	Total CO2 emissions
-	Grass	Carbon budget
-	Grass growth	BECCS, DAC
Individual	Herdsman	-
Perceived severity of the problem	Ecological value	Attitude regarding climate change action
Peer pressure in opinion regarding a problem	Peer pressure in adding or removing cows	Peer pressure regarding climate change action

6.4 Contribution to existing theory

The ACT model contributes to the existing theory of critical transitions in society (Scheffer et al., 2003).

Firstly, it made the relation between the critical transition theory and the energy transition and elaborated the model with new elements. By doing so, the transition trajectory of the energy transition could be learned about.

Secondly, it explicitly modelled the effects of behavioral dynamics of individuals on the energy transition in an ABM. By doing so, a lot of new causes of critical transitions were found, see paragraph 6.1.

The AToC model contributes to the existing literature about the energy transition and the Tragedy of the Commons (Schindler, 2012).

Firstly, the existing model was adapted and elaborated on with new elements to be more useful for an analogy with the energy transition.

Secondly, the model provided building blocks for a narrative regarding the energy transition, see paragraph 6.2.

6.5 Future research

Future research can relate the Tragedy of the Commons more to the energy transition. By doing so, the theory of the Tragedy of the Commons can be further linked to the energy transition to find more potential building block for a narrative about the energy transition. It can be further linked by replacing the grass growth function by a BECCS/DAC growth function. This is because when there is more BECCS/DAC the carbon budget grows back.

7. CONCLUSION

In this conclusion, the answer to the research question is given. The main research question was:

What can we learn from simple agent-based models about the effects of behavioral dynamics of individuals on the energy transition, using the concepts of critical transitions and the Tragedy of the Commons?

This main research question is answered by answering the sub questions. The first two sub questions were:

1. *How can we relate Scheffers's critical transition model to the energy transition by replicating and extending the model using agent-based modelling?*
2. *How can we relate Schindler's Tragedy of the Commons model to the energy transition by adapting and extending the model using agent-based modelling?*

To answer these questions, criteria were created for the newly created models. These criteria were:

1. The model must have a link with the energy transition.
2. The model must have a nice balance between being representative enough of the complexity of the energy transition and being simple enough to understand the results of the model.
3. The model must be an ABM, which can model non-rationality and complexity.

To fit this criteria the critical transition model (Scheffer et al., 2003) was adapted to an agent-based model called ACT. The original critical transition model describes the transition trajectory of changes in attitude regarding a problem. It can also describe changes in attitude regarding climate change.

The model was extended with the properties of a social network of the agents, heterogeneity in attitude of the agents, the possibility to include leaders with more influence in the model and the possibility of a neutral attitude of an agent instead of only an active or passive one.

The Tragedy of the Commons model (Schindler, 2012) also was adapted into the AToC model to better fit these criteria. The original Tragedy of the Commons model describes the behavior of herdsmen regarding a finite grass, which can be overgrazed. This can be related to energy transition because both describe the behavior regarding a common pool resource. In the ToC, the common pool resource is the grass while regarding the energy transition the common pool resource is the carbon budget. When a herdsman has more cows, it earns more profit but then the grass field gets overgrazed faster. In the same way, a country with more fossil fuel use, does have more profit but then the carbon budget reduces faster.

The model was extended with the possibility of the herdsmen to have a heterogeneous ecological value, which describes how much the herdsman cares about the grass outside of short-term profit. Besides, the AToC model gives the new possibility of incomplete information about the state of the grass. Also, the original model was adapted to give herdsmen with more cows more interest in keeping the grass because they had more to lose than someone with less cows. Lastly, the herdsmen can switch between multiple dispositions over time instead of only acting on one.

The third sub question was:

3. *How can the results of the agent-based models be explained in relation to the energy transition?*

ACT model

Results of the ACT model showed that the results of the original critical transition model could be reproduced in an ABM. The cost of deviation regarding the energy transition, can be explained as more than only peer pressure, which Scheffer uses in his model. For example, habit, limited cognitive resources, information bubbles, imitation and contagion in behavior all cause it to be hard to deviate from the average action regarding climate change.

Besides, results of this model showed that in case of the addition of a neutral attitude the inertia due to cost of deviation strongly reduces. Regarding the energy transition this can be explained as that when small steps are possible, it takes less cost of deviation due to habit, limited cognitive resources, vested interest and peer pressure.

While in case of adding leaders, the inertia strongly increases, which is different than the predictions of Scheffer et al. (2003). He predicted that leaders would catalyze change by convincing others to change. However, by explicitly modeling leaders it showed that there not only exist leaders who catalyze change but also leaders who counteract change. These leaders cause inertia to strongly increase. These leaders who counteract change can be explained as vested interest of fossil fuel companies.

Introducing a simple social network of peers who influence an agent instead of the average public opinion reduced the inertia in changes in public attitude. In the energy transition individuals are often influenced by their peers. For example, an individual is more likely to buy solar panels not because of the average number of solar panels per household in a country but because of what his neighbor does. There can occur bubbles of people with the same attitude regarding climate change when there is a high cost of deviation.

Lastly, adding heterogeneity in the attitude of the agents reduced inertia in change, which was also predicted by Scheffer et al. (2003). However, it does not necessary have to be the case that heterogeneity in attitude reduces inertia regarding climate change. Heterogeneity causes there to be positive as well negative outliers. It is the question whether these two offset each other.

There are several arguments for a smooth and a critical transition in attitude regarding climate change.

The arguments for a smooth transition are:

1. Humans are often influenced by their peers and not by the average public opinion.
2. There are some leaders who try to change attitudes regarding climate change.
3. Small steps to change climate change are possible.

The arguments for inertia and a sudden shift are:

1. Vested interest may influence agents to have a passive attitude regarding climate change until the problem reaches a tipping point.
2. Society continues emitting carbon emissions because of habit, limited cognitive resources, imitation and contagion in behavior.

AToC model

The results of the AToC model showed that slow adaptation of the herdsmen to changing circumstances caused the grass to be more overgrazed. This slowness in adaptation can be explained by limited cognitive resources and ingrained behaviors of humans. Regarding the energy transition this can be explained that the slow ability of society to adapt makes it more likely that a tragedy will happen.

Another result of the AToC model was that different perceptions of the state of the grass by the herdsmen caused them to own a different number of cows. Herdsmen who perceived there was little grass available did have less cows than herdsmen who perceived there was more grass available. This can be explained by that countries who do not perceive the climate change problem as a severe one, will put less effort in reducing emissions than countries who do perceive is as a severe problem. This causes some countries to put in more effort than others. A possible explanation of the different perceptions is that in some countries it is easier to see the implications of climate change.

Also, heterogeneity in the level of environmentalism of the herdsmen caused them to own different number of cows. This does have an almost similar interpretation. The explanation is that countries who care more about climate change will act more on it. This could cause that some countries will be free riders.

When the herdsmen were initialized to sometimes act based on conformity, it was more likely that the grass was overgrazed. The herdsmen did continue adding cows because other herdsmen did, even though they themselves wanted to reduce cows. Regarding the energy transition conformity is the cost of deviation from the average. The cost of deviation from the average is caused by vested interests, limited cognitive resources, imitation and habit. This cost of deviation contributes to the possibility of a tragedy regarding climate change.

The last sub question was:

4. *How do the insights regarding the energy transitions compare between those models?*

Both models investigated the effects of heterogeneity of the perceived seriousness of the problem and the effects of cost of deviation.

The results of heterogeneity of the perceived seriousness of the problem contradicted each other. The ACT model showed that heterogeneity in the perceived seriousness of the problem caused there to be less inertia. This happened because the positive outliers took early action. However, the AToC model showed that heterogeneity in environmentalism caused a tragedy to be more likely. This was caused by negative outliers who added a lot of cows even though the grass was on a tipping point of collapse. Therefore, it is concluded that based on these models it is unclear whether heterogeneity in the perceived seriousness contributes to climate change. It depends on whether the positive outliers do have more effect than the negative outliers. This contradicts Scheffer et al. (2003) who predict that heterogeneity in the perceived seriousness of the problem causes there to be less inertia in attitudinal change of society when there is a high cost of deviation.

In both models, the effects of cost of deviation contributed to climate change. It caused the agents to do the same as other agents due to habit, imitation, peer pressure, limited cognitive resources and contagion in behavior. This gives an extra verification of the results.

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APPENDIX

APPENDIX A: Critical transition model Scheffer

A1. Mathematical description of the model

Let *U(+)* denote the perceived utility for being active and *U(-)* the utility of being passive. These utilities have a random component to reflect differences across people:

$\widetilde{U}(a) = U(a) + s\epsilon(a)$ for action $a = +1$ *or* $a = -1$,

where *U(a)* does not involve randomness, ϵ(a) is a random variable, and *s* scales the variance. It turns out that if ϵ(a) is independently and identically distributed across people and action, the law of large numbers may be applied and compute the probability P of action a as a function of *U(a)*, *a*, and *s*:

$$P(a) = \frac{e^{\frac{U(a)}{s}}}{e^{\frac{U(+1)}{s}} + e^{\frac{U(-1)}{s}}}.$$

The perceived utility of action a by individual *i* denoted as $U(a_i)$ is now also affected by social pressure. The cost of deviating from the overall tendency of action is $c(a_i - A)^2$. Then the perceived utility of individual *i* including the cost of social pressure becomes:

$$V_t(a_i) = U_t(a_{i,t}) - c\left(a_{i,t} - A_t\right)^2.$$

Let the overall tendency for action *A* at time *t* be:

$$A_t = P_t(+1) - P_t(-1).$$

If in the probability functions *U* is replaced with *V* then the overall tendency for action *A* becomes (see appendix):

$A_t = T\left(\frac{h_t + 2cA_{t-1}}{s}\right)$, with $h_t = \frac{U_{t(+1)} - U_{t(-1)}}{2}$ and $T_x = \frac{e^x - e^{-x}}{e^x + e^{-x}}$.

A2. Derivation equation Scheffer

$$A = P(+) - P(-)$$

$$= \frac{e^{\frac{U(+)-c(1-A)^2}{s}} - e^{\frac{U(-)-c(-1-A)^2}{s}}}{e^{\frac{U(+)-c(1-A)^2}{s}} + e^{\frac{U(-)-c(-1-A)^2}{s}}}$$

$$= \frac{e^{\frac{U(+)-c+2cA-cA^2}{s}} - e^{\frac{U(-)-c-2cA-cA^2}{s}}}{e^{\frac{U(+)-c+2cA-cA^2}{s}} + e^{\frac{U(-)-c-2cA-cA^2}{s}}}$$

$$= \frac{e^{\frac{U(+)+2cA}{s}} - e^{\frac{U(-)-2cA}{s}}}{e^{\frac{U(+)+2cA}{s}} + e^{\frac{U(-)-2cA}{s}}}$$

$$= \frac{e^{\frac{-U(+)-U(-)}{2}}}{e^{\frac{-U(+)-U(-)}{2}}} \times \frac{e^{\frac{U(+)+2cA}{s}} - e^{\frac{U(-)-2cA}{s}}}{e^{\frac{U(+)+2cA}{s}} + e^{\frac{U(-)-2cA}{s}}}$$

$$= \frac{e^{\frac{\frac{U(+)-U(-)}{2}+2cA}{s}} - e^{\frac{\frac{-U(+)+U(-)}{2}-2cA}{s}}}{e^{\frac{\frac{U(+)-U(-)}{2}+2cA}{s}} + e^{\frac{\frac{-U(+)+U(-)}{2}-2cA}{s}}}$$

$$= T\left(\frac{h + 2cA}{s}\right)$$

$$T = \tanh(x) = \frac{e^{x} - e^{-x}}{e^{x} + e^{-x}}$$

$$h = \frac{U(+) - U(-)}{2}$$

APPENDIX B: ACT model description

B1. Purpose

The purpose of this ABM is to learn about the behavioral dynamics of individuals regarding climate change action. More specific, the characterization of a transition, smooth or a sudden shift, and the effect of peer pressure in a social network, leadership, heterogeneity in opinion and the effect of continuous opinions instead of binary opinions. Besides, the results of the original model (Scheffer et al., 2003) are replicated in an ABM instead of a mean-field approach. In this way, the effect of non-rationality of the agents and complexity due to interaction between the agents are investigated.

B2. Entities and state variables

The model consists of 250 agents, which represent abstract individuals. Each individual has an opinion regarding a problem, which can be active or passive. The individuals do have a physical location on a 10 x 25 grid. Each individual has a utility for having an active opinion and one for a passive opinion. They feel a cost for deviating from the average public opinion, which is called the peer pressure sensitivity.

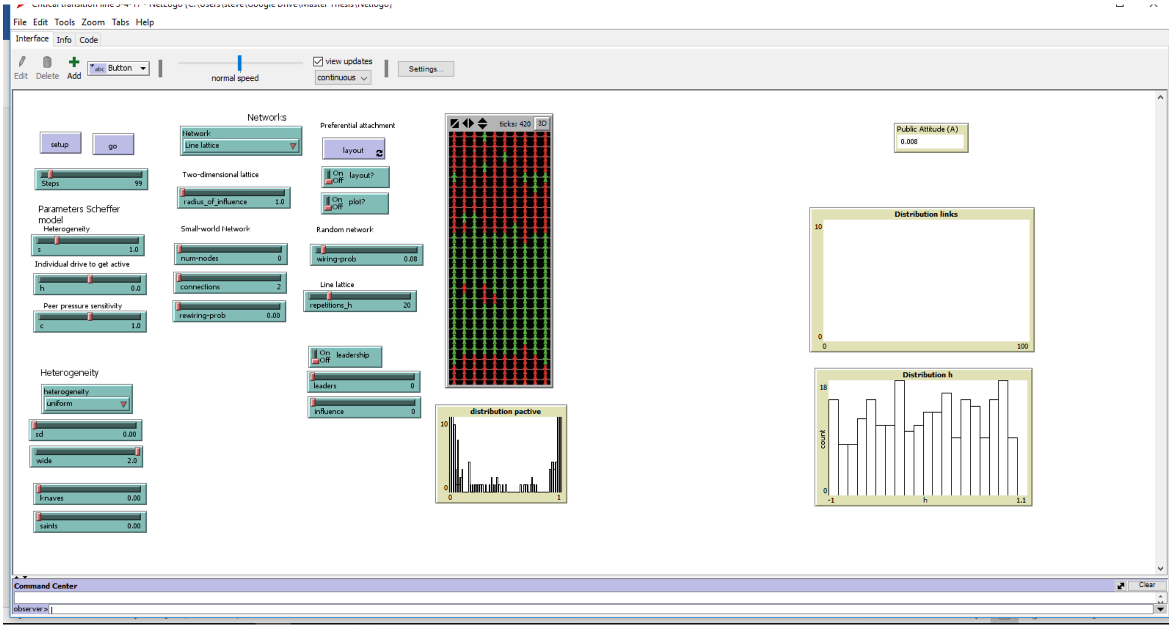
This model is extended with a few elements. The individuals are given a social network. Now, they feel a cost of deviation towards their social network instead of the average public opinion. Another extension is that the individuals can have a neutral opinion and have a utility for being neutral. Finally, the agents can be a leader, which have more peer pressure on others.

Table 7 Description of the state variables of an agent in the ACT model

State variable:	Description:	Properties:
Active	Describes the opinion of the agent regarding a problem, which can be active or passive. Extension 2: the agent can also have a neutral opinion regarding a problem.	$a_i = -1$ (passive) or $a_i = 1$ (active) Extension 2: $a_i = 0$ (neutral)
Utility active	The utility of an agent for having an active opinion regarding a problem.	$U_{active} \in [0,4]$
Extension 2: Utility neutral	The utility of an agent for having a neutral opinion regarding a problem.	$U_{neutral} \in [1,3]$
Utility inactive	The utility of an agent for having a passive opinion regarding a problem.	$U_{inactive} = 2$
Peer pressure sensitivity	Describes how much influence the average public opinion of all agents has on the agent due to peer pressure. Extension 1: Describes how much influence the average public opinion of the links has on the agent due to peer pressure.	$0 \leq c \leq 1$ Extension 3: or $c = 5$ (leader)
Physical location	Describes the location of an agent on a 10x25 grid.	$x_{cord} \in \{0,1,2,\ldots,9\}$ $y_{cord} \in \{0,1,2,\ldots,24\}$

Extension 1: Links of agent	Describes to which other agents the agent is connected and feels pressure from.	Links of agent=list of agents
Extension 3: Leader	Describes whether the agent is a leader or not	Leader=1 (normal agent) Leader>1 (leader agent)

B3. Netlogo implementation ACT



☑ view updates: continuous

Steps 99

s 1.0

h 0.0

c 1.0

heterogeneity: uniform

sd 0.00

wide 2.0

knaves 0.00

saints 0.00

Network: Line lattice

radius_of_influence 1.0

num-nodes 0

connections 2

rewiring-prob 0.00

layout? On/Off

plot? On/Off

wiring-prob 0.08

repetitions_h 20

leadership On/Off

leaders 0

influence 0

Public Attitude (A) 0.008

Figure 19 Implementation of the ACT model in Netlogo

B4. Process overview and scheduling

Setup:
- Setup individuals

Go:
- Repeat 40 times:
    - Increase utility for being active
    - Repeat 20 times:
        - Decision-making
    - Report new public opinion
- Repeat 40 times:
    - Decrease utility for being active
    - Repeat 20 times:
        - Decision-making
    - Report new public opinion

B5. Sub models

To setup

clear-all
reset-ticks

- All previous tasks are reset

set Inaction 2

- The utility for being inactive is set at 2

set h -1

- Initially the perceived seriousness of the problem is set at -1

setupindividuals

- All the individuals are created (see next sub model)

set A (sum [active] of individuals)/ count individuals

- The initial average public opinion is calculated

End

To setup individuals

```
if (Network = "Mean-field" ) [
    set agents (max-pxcor - min-pxcor + 1) * (max-pycor - min-pycor + 1)
    create-individuals agents [set active -1 set color Red set shape "person" while [any? other
    turtles-here][setxy random-pxcor random-pycor]
      if (heterogeneity = "homogeneous") [set Uaindividual 2 * h + Uinactief]
      if (heterogeneity = "uniform") [let h1 h + (- wide / 2 + random-float wide) set
Uaindividual 2 * h1  + Uinactief ]]
    if leadership [ask individuals [set leader 1] ask n-of leaders individuals [
          set leader influence set size 1.5]]]
```

- In this case there is no social network and the individuals are influenced by the average public opinion (mean-field). First, the number of agents are calculated. Then, they are given a shape and given a physical location on the 10x25 grid. The opinion of the agents can be set homogeneous or heterogeneous. Also, there can be set whether there are leaders, and the size of the peer pressure from him.

```
if (Network = "Mean-field continuum") [
    set agents (max-pxcor - min-pxcor + 1) * (max-pycor - min-pycor + 1)
    create-individuals agents [set active -1 set color Red set shape "person" while [any? other
          turtles-here][setxy random-pxcor random-pycor]
      if (heterogeneity = "homogeneous") [
         set Uaindividual 2 * h + Uinactief
         set unindividual h + Uinactief]]]
```

- In this case there is also a possibility to have a neutral opinion regarding the problem. The utility of having a neutral opinion is set the average of the passive and active utility.

```
if (Network = "Physical") [
    set agents (max-pxcor - min-pxcor + 1) * (max-pycor - min-pycor + 1)
    create-individuals agents [set active -1 set color Red set shape "person" while [any? other
    turtles-here][setxy random-pxcor random-pycor]
      if (heterogeneity = "homogeneous") [set Uaindividual 2 * h + Uinactief]
```

```
      if (heterogeneity = "uniform") [let h1 h + (- wide / 2 + random-float wide)
          set Uaindividual 2 * h1 + Uinactief ]]
    ask individuals [create-links-with other individuals with [
          distance myself <=radius_of_influence]]]
```

- In this case the agents have a social network. The agents do have links with all other agents within a distance smaller than a certain radius.

End

To go

```
      if (ticks <= 41 * repetitions_h and ticks != 0) [set h precision (h + 0.05) 3 ask individuals [
          set Uaindividual 2 * h + Uinactief
          set Unindividual h + Uinactief]]
      if (ticks > 40 * repetitions_h) [set h precision (h - 0.05) 3 ask individuals [
           set Uaindividual 2 * h + Uinactief
           set Unindividual h + Uinactief]]
      if (ticks = 81 * repetitions_h)[stop]
      repeat repetitions_h [decision-making]
```

End

- The perceived severity of the problem starts at -1 and is 40 times increased with 0.05. This causes the utilities for having an active opinion regarding the problem to change. After that, the perceived severity of the problem is decreased with 0.05 40 times. Each time the utilities are changed the decision-making process is repeated a certain amount of times.

To decision-making

```
    Tick
```

- The timer is set one tick further.

```
if (Network = "Mean-field") [
      if (leadership = FALSE) [set A (sum [active] of individuals)/ (count individuals)]
      if (leadership = TRUE) [set A (sum [active * leader] of individuals)/ (count individuals)]
      ask individuals [
        let r random-float 1
        set pindividual ( Exp ( ( Uaindividual - c * ( 1 - A ) ^ 2 ) / s ) ) /
   ( Exp ( ( Uaindividual – c  * ( 1 - A ) ^ 2 ) / s ) + Exp ( ( Uinactief - c * ( - 1 - A ) ^ 2 ) / s ) )
ifelse r < pindividual [set active 1 set color Green][set active -1 set color Red ]]]
```

- Again, this is the case were an individual is influenced by the average opion. The average public opinion is calculated. The agents have a probability for having an active attitude and a passive attitude. Each decision-making process they become active or passive dependent on a stochastic process.

```
if (Network = "Mean-field continuum")
      set A (sum [active] of individuals)/ (count individuals)
      ask individuals [
         let r random-float 1
         set pindividual ( Exp ( ( Uaindividual - c * ( 1 - A ) ^ 2 ) / s ) ) / ( Exp ( ( Uaindividual -
c * ( 1 - A ) ^ 2 ) / s ) + Exp(( Unindividual - c * ( A ) ^ 2 ) / s )+ Exp ( ( Uinactief - c * ( - 1 -
A ) ^ 2 ) / s ) )
         set pnindividual ( Exp ( ( Unindividual - c * ( A ) ^ 2 ) / s ) ) / ( Exp ( ( Uaindividual - c
* ( 1 - A ) ^ 2 ) / s ) + Exp(( Unindividual - c * ( A ) ^ 2 ) / s )+ Exp ( ( Uinactief - c * ( - 1 - A
) ^ 2 ) / s ) )
```

```
    if (r < pindividual) [ set active 1 set color Green]
    if (r > pindividual and r < pindividual + pnindividual)[set active 0 set color Yellow]
    if (r > pindividual + pnindividual)[set active -1 set color Red]]]
```

- In this case, there is also a probability that an agent has a neutral opinion. The neutral opinion is less sensitive to peer pressure because it deviates less from the average public opinion.

```
if (Network = "Physical") [
  set A (sum [active] of individuals)/ count individuals
  ask individuals [
    let r random-float 1
    ifelse (count link-neighbors = 0)[set Aindividual active ][set Aindividual sum [active] of link-neighbors / count link-neighbors]
    set pindividual ( Exp ( ( Uaindividual - c * ( 1 - Aindividual ) ^ 2 ) / s ) ) / ( Exp ( ( Uaindividual - c * ( 1 - Aindividual ) ^ 2 ) / s ) + Exp ( ( Uinactief - c * ( - 1 - Aindividual ) ^ 2 ) / s ) )
    ifelse r < pindividual [ set active 1 set color Green][set active -1 set color Red ]]]
```

- In this case, the agents have a social network. The agents are now influenced by the average opinion of the links of the agent.

End

APPENDIX C: ACT model: parameter settings experiments

Table 8 Parameter settings of the experiments done on the ACT model

	Experiment 1: Mean-field	Experiment 2: Nearest neighbors	Experiment 3: Heterogeneity	Experiment 4: Leaders	Experiment 5: Continuity
S	1.0	1.0	1.0	1.0	1.0
H	-1.0	-1.0	-1.0	-1.0	-1.0
C	0, 0.5, 1	0, 0.5, 1	0, 0.5, 1	0, 0.5, 1	0, 0.5, 1
Repetitions_h	20	20	20	20	20
Network	Mean-field	Geographical	Mean-field	Mean-field	Mean-field
Radius of peers	n.a.	0,1,2,4,10,50	n.a.	n.a.	n.a.
Heterogeneity	Homogeneous	Homogeneous	Uniform	Homogeneous	Homogenous
Wide	n.a.	n.a.	0,0.5,1,1.5,2	n.a.	n.a.
Leadership	False	False	False	True	False
# Leaders	n.a.	n.a.	n.a.	0,10,20,50	n.a.
Influence of leaders	n.a.	n.a.	n.a.	5	n.a.
Continuity	False	False	False	False	True
Attitude of agents	Binary	Binary	Binary	Binary	+/0/– or ++/+/0/-/--
Repetitions	10	10	10	5	10
Agents	250	250	250	250	250

APPENDIX D: ACT model: results

D1. ACT model: peer pressure in a physical network

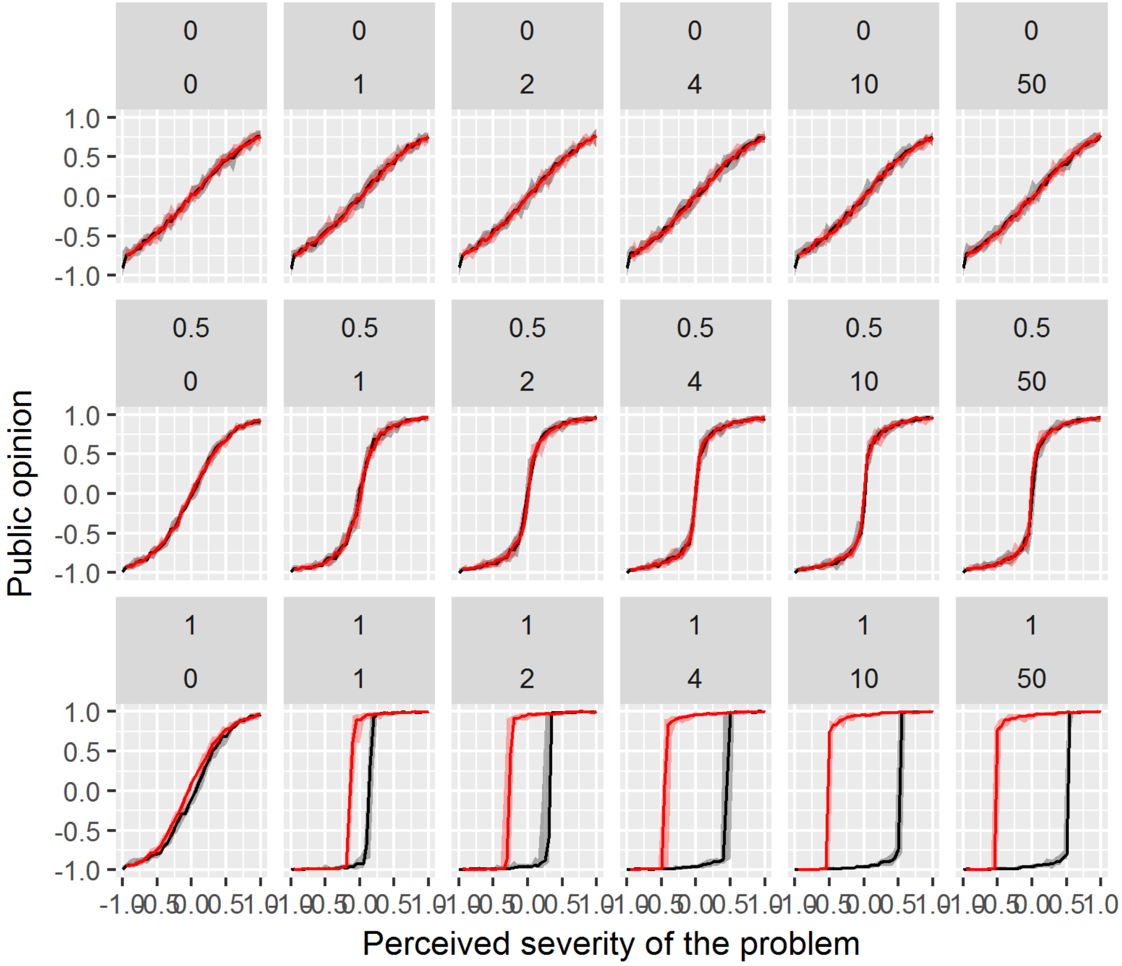


Figure 20 Peer pressure in a physical network. The number above each time is the peer pressure sensitivity and the number below the radius within which agents are connected.

D2. ACT model: heterogeneity in attitude

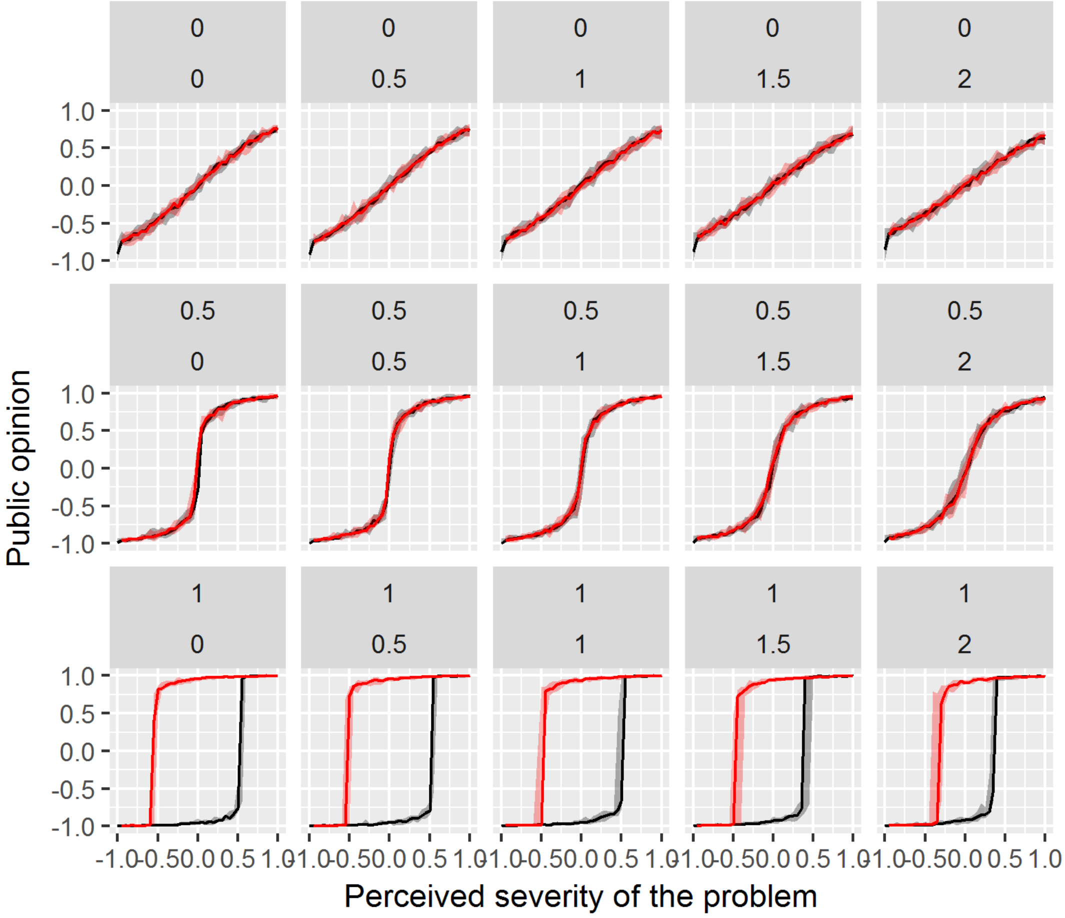


Figure 21 Heterogeneity in attitude is modelled in this experiment. The number above is the peer pressure sensitivity and the number below the bandwidth of the heterogeneity in attitude.

D3. ACT model: leaders

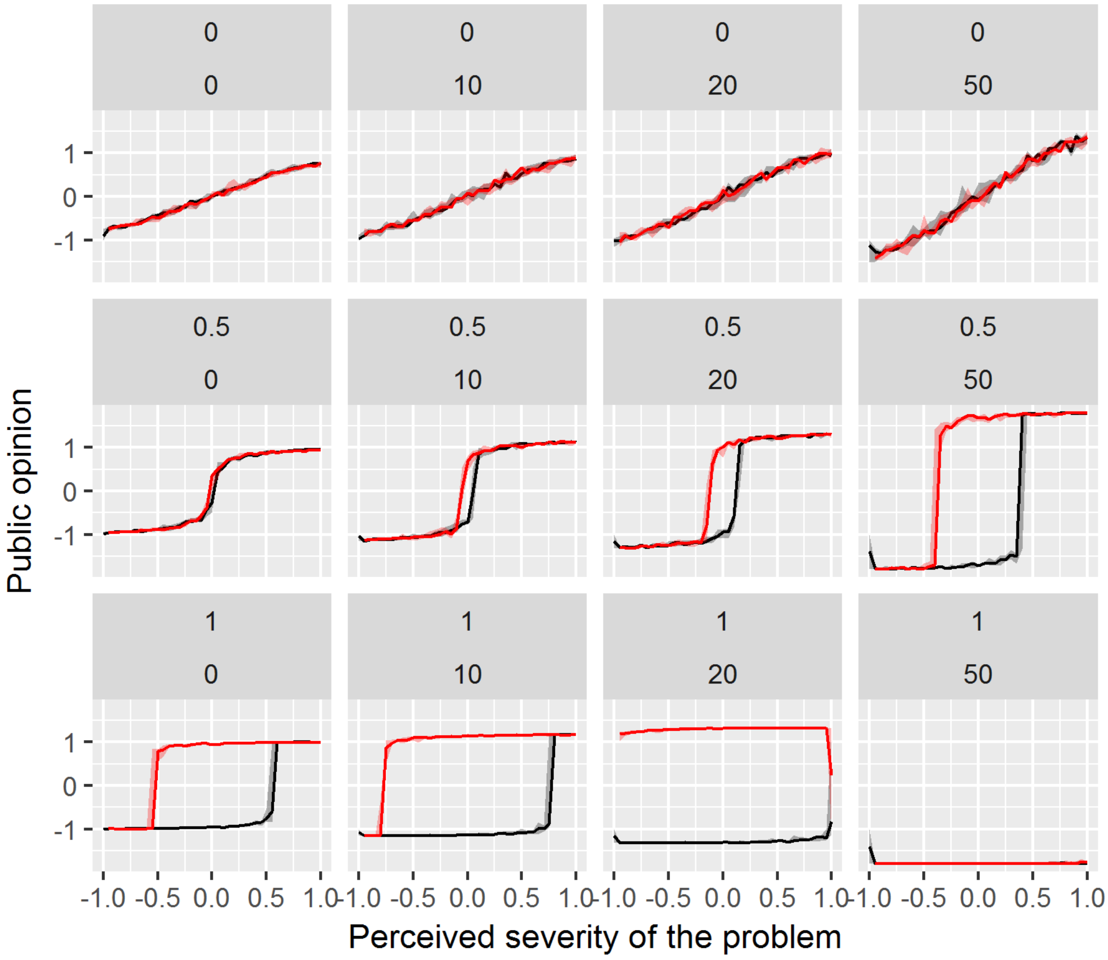


Figure 22 In this figure, the experiment with leaders is showed. The number above is the peer pressure sensitivity and the number below the number of leaders.

D4. ACT model: continuity in attitude

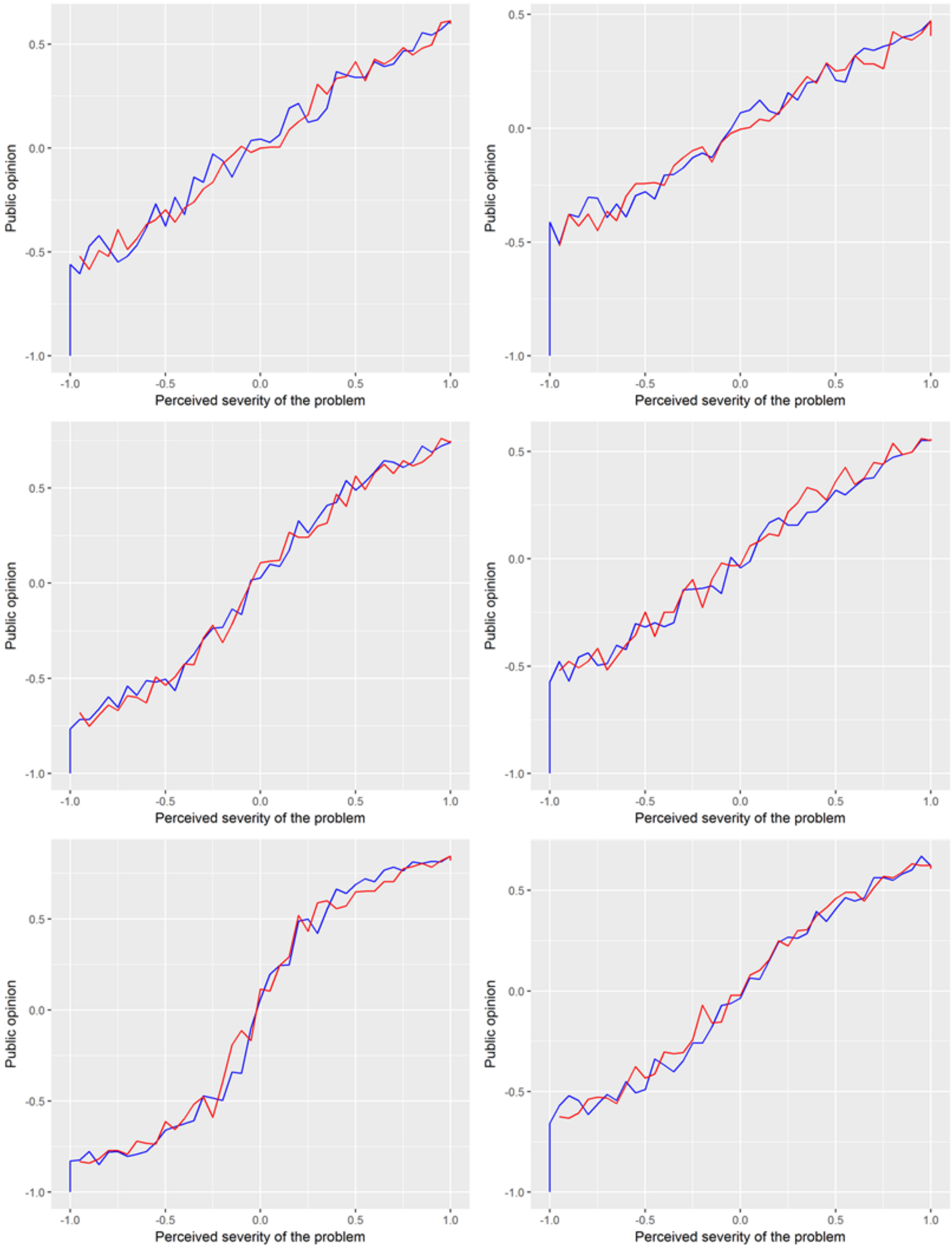


Figure 23 One run of when agents have 3 modes of attitude (left) and one run when agents have 5 modes of attitude (right). There is a mean-field approach used within the ACT model. Above is with low peer pressure sensitivity and below with high peer pressure sensitivity.

APPENDIX E: AToC model description

E1. Purpose

The purpose of this model is to learn about the behavioral dynamics of herdsmen in the Tragedy of the Commons to learn more about the behavior regarding the energy transition. In this way, potential building blocks can be found for narratives regarding the energy transition. The effects of selfishness, conformity and heterogeneity in ecological value are investigated.

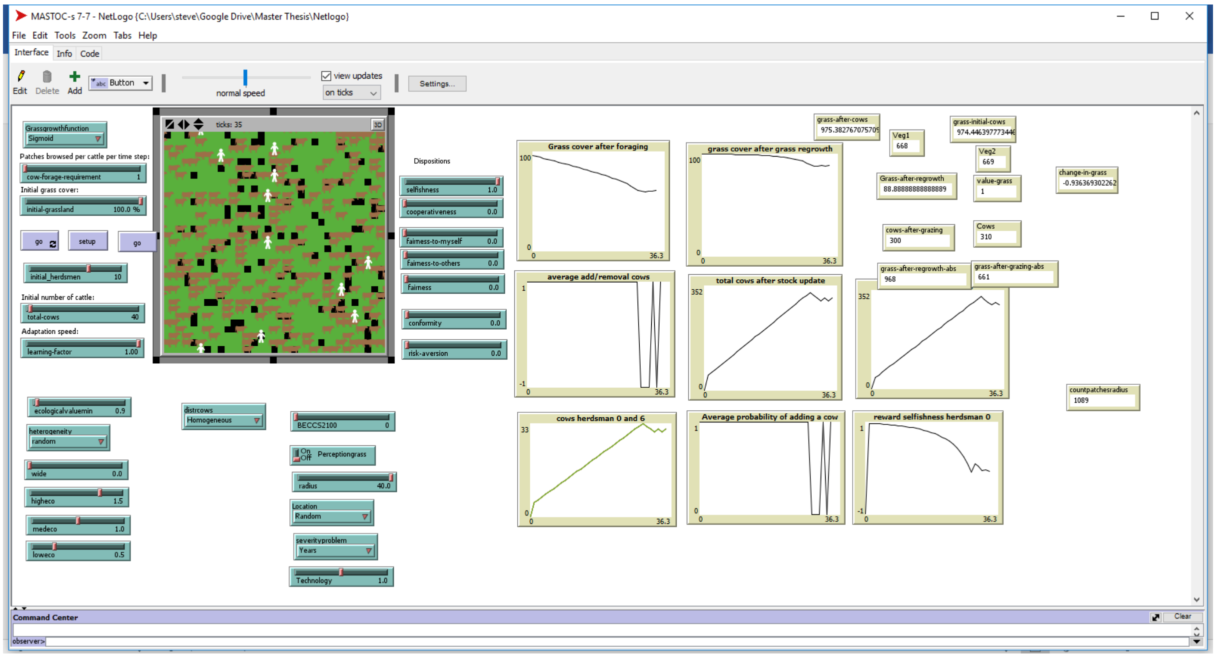
E2. Entities and state variables

The model consists of herdsmen, cows and grass. They are placed on a 33 x 33 grid. There are 10 herdsmen with a physical location on the grid and each of them has their own cows. The herdsmen each have a level of environmentalism. Besides that, they have levels of the dispositions selfishness and conformity. The cows have a physical location on the grid. There are 1089 land patches and they can be in a grass or non-grass state.

Table 9 Description of the state variables of a herdsman in the AToC model

State variable:	**Description:**	**Properties:**
Cows owned (k_i)	The number of cows the herdsman owns	$k_i \epsilon \mathbb{N}$
Change cows (x_i)	Describes whether the herdsman added or removed a cow last turn	$x_i = 1 \vee x_i = -1$
Ecological value ($v_{eco,i}$)	Describes how much the herdsman cares about the grass outside of short term economic profit	$v_{eco,i} \epsilon [0,3]$
Probability add	Describes the probability that the herdsman will add a cow	$0 \le P_{add} \le 1$
Probability subtract	Describes the probability that the herdsman will remove a cow	$0 \le P_{subt} \le 1$
Disposition	Describes on which disposition the herdsman gets a reward this tick	Disposition∈{Selfish, conformity}
Perceived grass	Describes how much grass the herdsman perceives there to be on all patches	0 ≤Perceived grass≤ 1089

E4. Netlogo implementation AToC



Grassgrowthfunction: Sigmoid

Patches browsed per cattle per time step:

cow-forage-requirement 1

Initial grass cover:

initial-grassland 100.0 %

initial_herdsmen 10

Initial number of cattle:

total-cows 40

Adaptation speed:

learning-factor 1.00

ecologicalvaluemin 0.9

heterogeneity: random

wide 0.0

higheco 1.5

medeco 1.0

loweco 0.5

distrcows: Homogeneous

BECCS2100 0

On/Off Perceptiongrass

radius 40.0

Location: Random

severityproblem: Years

Technology 1.0

selfishness 1.0

cooperativeness 0.0

fairness-to-myself 0.0

fairness-to-others 0.0

fairness 0.0

conformity 0.0

risk-aversion 0.0

grass-after-cows 975.382767075709

Veg1 668

grass-initial-cows 974.446397773446

Veg2 669

Grass-after-regrowth 88.8888888888889

value-grass 1

change-in-grass -0.936369302262

cows-after-grazing 300

Cows 310

grass-after-regrowth-abs 968

grass-after-grazing-abs 661

countpatchesradius 1089

Figure 24 The Netlogo implementation of the AToC model.

E4. Process overview and scheduling

Setup:
- Create initial grass
- Create herdsmen
- Create initial cows

Go:
- Graze
- Grass-regrowth
- Update stock

E5. Sub models

To setup

```
clear-all
reset-ticks
```

- All previous actions are reset

```
ask n-of round (initial-grassland / 100 * count patches) patches [ set pcolor green ]
```

- A certain percentage of patches in initialized to be grass.

```
create-herdsmen initial_herdsmen [ set color white set size 2 set shape "person"
  if (Location = "Random") [move-to one-of patches]]
ask herdsmen [ set xi one-of (list -1 1) set Prob-add 0.5 set Prob-subtract 0.5 set disposition 0]
if (heterogeneity = "random") [ask herdsmen [set ecologicalvaluei ecologicalvaluemin - wide
/ 2 + random-float wide ]]
set conformity precision (1 - selfishness) 2
```

- A certain number of herdsmen are created, each is located on a random patch. Their action is initialized randomly to add or remove a cow, their probability to add or remove a cow is set at 0.5 and initially they don't have a psychological disposition. The ecological value is set homogeneous or heterogeneous with an uniform random distribution. The conformity and selfishness of the agents is set exogenous.

```
create-cows total-cows [ move-to one-of patches set color brown set size 2 set shape "cow" ]
while [ any? cows with [ owner = 0 ] ] [
 if (distrcows = "Homogeneous") [ask one-of cows with [owner = 0] [set owner min-one-of
herdsmen [ki]] ask herdsmen [set ki count cows with [owner = myself]]]]
set K total-cows
```

- A certain number of cows are created and homogeneously spread across the herdsmen. Besides, the total number of cows *K* is calculated.

End

To go

```
  graze
  grass-regrowth
  update-stock
  tick
```

```
  if ticks = 300 [ stop ]
```

- First, the cows graze, then the grass does regrow. After that, the herdsmen decide to add or remove a cow. Then, the timer is set one tick further. After 300 ticks, the model run stops.

End

To graze

```
ask cows [ set forage 0 ]
```

- The cows have not eaten anything.

```
ask cows [
while [ (forage < cow-forage-requirement) and (any? patches with [ pcolor = green ]) ] [
move-to min-one-of patches with [ pcolor = green ] [ distance myself ]
ask patch-here [ set pcolor black ]
set forage forage + 1]
if forage < cow-forage-requirement [die]]
```

- The cow moves to the closest grass field and eats it. The grass field turns into non-grass. The cow stops eating when it has reached it forage requirement. If there is no grass left the cow dies.

```
set grass-after-grazing count patches with [ pcolor = green ] / count patches * 100
set grass-after-grazing-abs count patches with [pcolor = green]
set cows-after-grazing count cows
```

- The grass after grazing and the cows after grazing are calculated.

End

To grass-regrowth

```
set Veg count patches with [ pcolor = green ]
set maxV count patches
```

- The number of patches with grass on it and the total number of patches are calculated.

```
if (grassgrowthfunction = "Sigmoid") [
  set grass-growth round ((maxV - Veg) / (1 + Exp(-0.008 * (Veg - 545))))
ask n-of min (list grass-growth count patches with [ pcolor = black ]) patches with [ pcolor = black ] [ set pcolor green ]]
```

- A certain number, calculated by the grass growth function, of the non-grass fields are turned into grass. When the grass growth is more than the non-grass patches, all patches turn into grass.

```
ask herdsmen [set grass-after-regrowth-in-radius-i count patches with [pcolor = green and distance myself <= radius]]
set countpatchesradius count patches with [(distancexy 0 0) <= radius]
ask herdsmen [set grass-after-regrowth-perc round (grass-after-regrowth-in-radius-i * count patches / countpatchesradius)]
```

- When there is incomplete information the herdsmen perceive the grass in a certain radius from their location. They extrapolate this number to the perception of all the grass fields.

```
set grass-after-regrowth count patches with [pcolor = green] / count patches * 100
set grass-after-regrowth-abs count patches with [pcolor = green]
```

- The grass after regrowth is calculated.

End

To update-stock

```
if (grassgrowthfunction = "Sigmoid")[
ifelse (K = 0)
  [ask herdsmen [set price-grass ecologicalvaluei]]
  [ask herdsmen [set price-grass (ki / (cow-forage-requirement * K) + ecologicalvaluei)]]
ask herdsmen [ set fin-reward-single (xi - change-grass (cows-after-grazing) (cows-after-grazing + xi)(who) * price-grass )]]
```

- Each herdsman calculates their reward for their selfish disposition for their last behavior. The change-grass function, calculates the effects on the number of grass fields due to adding or removing one cow by the herdsman.

```
ask herdsmen [
if (fin-reward-single > 0) [ set reward-single 1 ]
if (fin-reward-single < 0) [ set reward-single -1 ]]
```

- The reward of each herdsman is rounded to 1 or -1.

```
ask herdsmen [
if (mean [ xi ] of other herdsmen < 0 and xi = -1) [ set reward-conf 1 ]
if (mean [ xi ] of other herdsmen > 0 and xi = 1) [ set reward-conf 1 ]
if (mean [ xi ] of other herdsmen < 0 and xi = 1) [ set reward-conf -1 ]
if (mean [ xi ] of other herdsmen > 0 and xi = -1) [ set reward-conf -1 ]
]
```

- Each herdsman calculates their reward for their conformity disposition for their last behavior.

```
ask herdsmen [set r random-float 1
if (r <= selfishness) [ set reward reward-single set disposition "selfishness"]
if (r > selfishness) [set reward reward-conf set disposition "conformity"]]
```

- Each tick of the model, the herdsmen do have a selfish or a conformity disposition. This is based on a stochastic process. When the herdsman does have a selfish disposition, they get the reward from the selfish disposition, and when they have a conformity disposition they get the reward from the conformity disposition.

```
ask herdsmen [
if (reward > 0 and xi = 1) [ set Prob-add Prob-add + (1 - Prob-add) * learning-factor set Prob-subtract 1 - Prob-add ]
if (reward < 0 and xi = 1) [ set Prob-add Prob-add * (1 - learning-factor) set Prob-subtract 1 - Prob-add ]
if (reward > 0 and xi = -1) [ set Prob-subtract Prob-subtract + (1 - Prob-subtract) * learning-factor set Prob-add 1 - Prob-subtract ]
if (reward < 0 and xi = -1) [ set Prob-subtract Prob-subtract * (1 - learning-factor) set Prob-add 1 - Prob-subtract ]]
```

- When the reward is larger than 0 it becomes more likely that the herdsman will repeat his action. When it is smaller the it becomes less likely that the herdsman will take the same action as the previous tick. The learning factor changes how fast the herdsman adapts to its rewards. In case the learning factor is 1 it will chose 100% of the times chose for the action with the best reward.

```
ask herdsmen [ifelse random-float 1.0 < Prob-add [ set xi 1 set ai 1 ] [ set xi -1 ] ]
ask herdsmen [ ifelse (xi = 1) [ hatch-cows 1 [ set owner myself set color brown set size 2 set
shape "cow" ] ]
[ ifelse (any? cows with [ owner = myself ]) [ ask one-of cows with [ owner = myself ] [ die ]
set ai -1][set ai 0] ] ]
```

- Based on their probability of adding a cow, the herdsmen add or remove one cow.

```
ask cows [ move-to one-of patches set color brown set size 2 set shape "cow" ]
ask herdsmen [ set ki count cows with [ owner = myself ] ]
set K sum [ki] of herdsmen
```

- The cows move to a random position, the herdsmen update the number of cows they own and the total number of cows are updated.

End

To-report change-grass [initial-cows after-cows number]

- This sub model calculates the effects of adding or removing a cow by a herdsman.

```
ifelse (Perceptiongrass = False)
[   set Veg1 grass-after-regrowth-abs - initial-cows * cow-forage-requirement
set Veg2 grass-after-regrowth-abs - after-cows * cow-forage-requirement]
```

- When the herdsmen have perfect knowledge about the grass, the grass after grazing is calculated with the total number of cows and the total number of cows plus or minus one cow.

```
[  set Veg1 [grass-after-regrowth-perc] of herdsman number - initial-cows * cow-forage-
requirement
  set Veg2 [grass-after-regrowth-perc] of herdsman number - after-cows * cow-forage-
requirement]
```

- When the herdsmen have imperfect knowledge about the state of the grass, the same is calculated only then with what each herdsman perceives the grass to be around his location.

```
if (Veg1 <= 0 or Veg2 <= 0)[set Veg1 20 set Veg2 Veg1 + (initial-cows - after-cows) * cow-
forage-requirement]
```

- In case the grass after grazing would be smaller then, which is not possible, the grass after is set at a small amount to prevent a bug.

```
if (grassgrowthfunction = "Sigmoid") [
set grass-initial-cows Veg1 + (count patches - Veg1) / (1 + Exp(-0.008 * (Veg1 - 545)))
set grass-after-cows Veg2 + (count patches - Veg2) / (1 + Exp(-0.008 * (Veg2 - 545)))
```

- It is calculated what would be the grass after grazing and regrowth, with the total number of cows and the total number of cows plus or minus one.

```
set change-in-grass grass-initial-cows - grass-after-cows]
report change-in-grass
```

- The difference between those two is the effect on the grass of adding or removing one cow.

End

APPENDIX F: AToC model: parameter settings experiments

Table 10 Parameter settings of the experiments done on the AToC model. In red are deviations compared to the fast adaptation experiment.

	Experiment 1: Fast adaptation	Experiment 2: Slow adaptation	Experiment 3: Perception grass	Experiment 4: Heterogeneity	Experiment 5: Conformity
Grass growth function	Adapted sigmoid curve	Adapted sigmoid curve	Adapted sigmoid curve	Adapted sigmoid curve	Adapted sigmoid curve
Cow forage requirement	1	1	1	1	1
Initial grassland	100%	100%	100%	100%	100%
Herdsmen	10	10	10	10	10
Initial cows	0	0	0	0	0
Distribution cows	n.a.	n.a.	n.a.	n.a.	n.a.
Ecological value	0.6, 1, 2	0.6, 1, 2	0.6, 1, 2	0.6, 1, 2	0.6, 1, 2
Adaptation speed	1	0.1	1	1	1
Perception grass	False	False	True	False	False
Perception grass radius	n.a.	n.a.	1, 2, 5, 50	n.a.	n.a.
Location	n.a.	n.a.	Random	n.a.	n.a.
Heterogeneity	Homogeneous	Homogeneous	Homogeneous	Uniform distribution	Homogeneous
Heterogeneity wide	n.a.	n.a.	n.a.	0, 0.5, 1, 2	n.a.
Selfishness	1	1	1	1	0.4
Conformity	0	0	0	0	0.6

APPENDIX G: AToC model: results

G1. AToC model: Explanation different behavior one run of heterogeneity in the ecological value of the herdsmen

In table 11 and figure 25, the run is shown with different behavior than the other runs in figure 15. The ecological values are randomly chosen between 0.1 and 1.1 but by change they are all very high in that run, which causes the different behavior compared to the other runs in figure 15. As a comparison, table 12 and figure 26 show another run, where the ecological values are not that high by chance.

Table 11: One of the ten runs of figure 14 with heterogeneity in ecological value with very high ecological values by chance.

Herdsman number	Ecological value
0	1.03
1	0.69
2	0.45
3	0.74
4	0.94
5	0.23
6	0.95
7	0.98
8	0.97
9	1.05

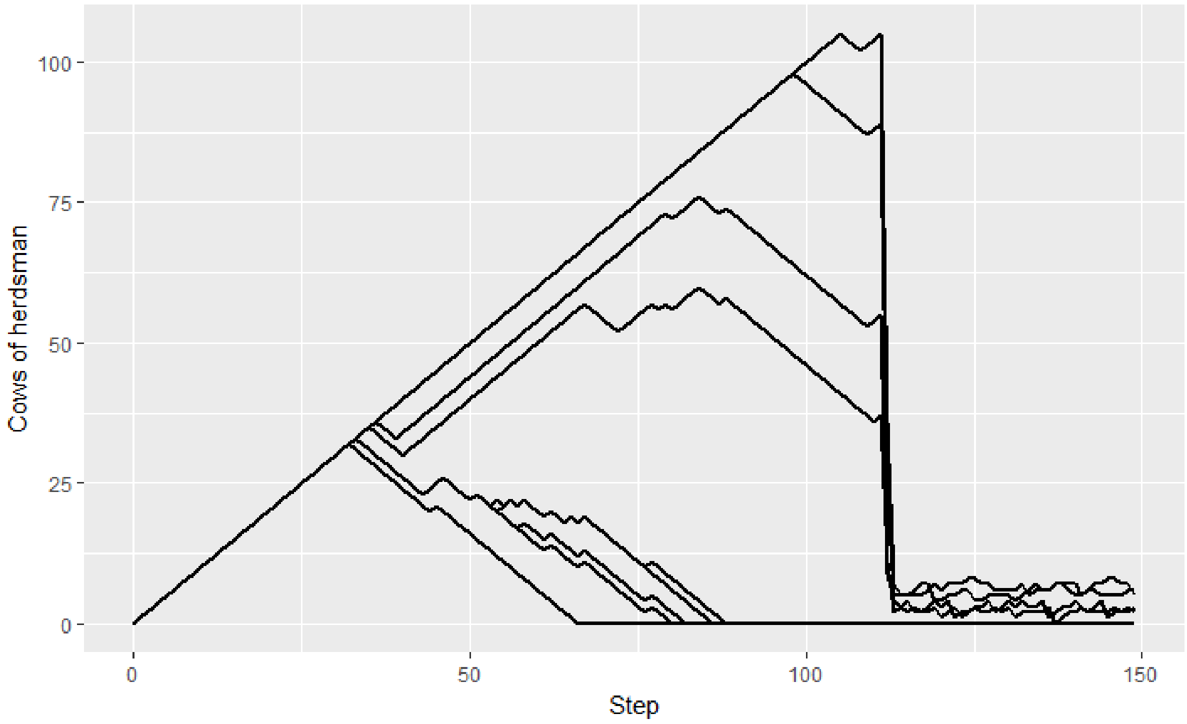


Figure 25: One of the ten runs of figure 14 and heterogeneity in the ecological values with very high ecological values by chance.

Table 12 One of the runs of heterogeneity in the ecological value.

Herdsman	Ecological value
0	0.40
1	0.99
2	0.67
3	0.75
4	0.20
5	0.80
6	0.48
7	0.99
8	0.29
9	1.06

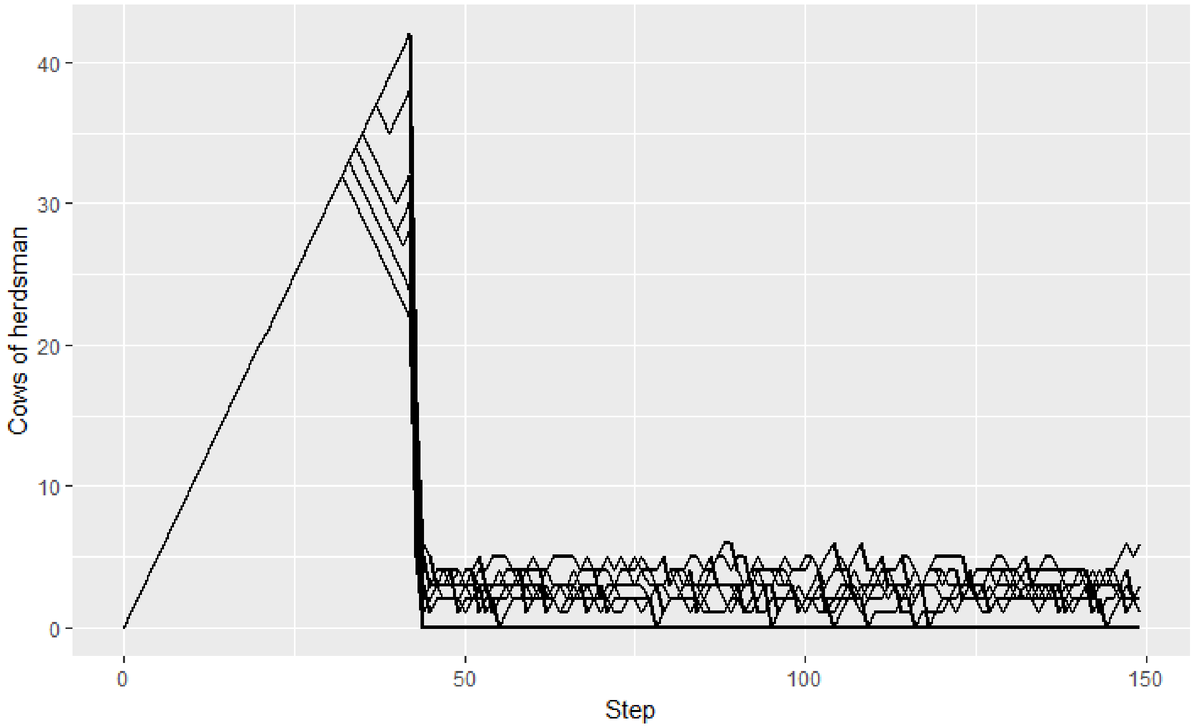


Figure 26 One of the runs of heterogeneity in the ecological value.

G2. AToC model: Effect of increased heterogeneity in the ecological value

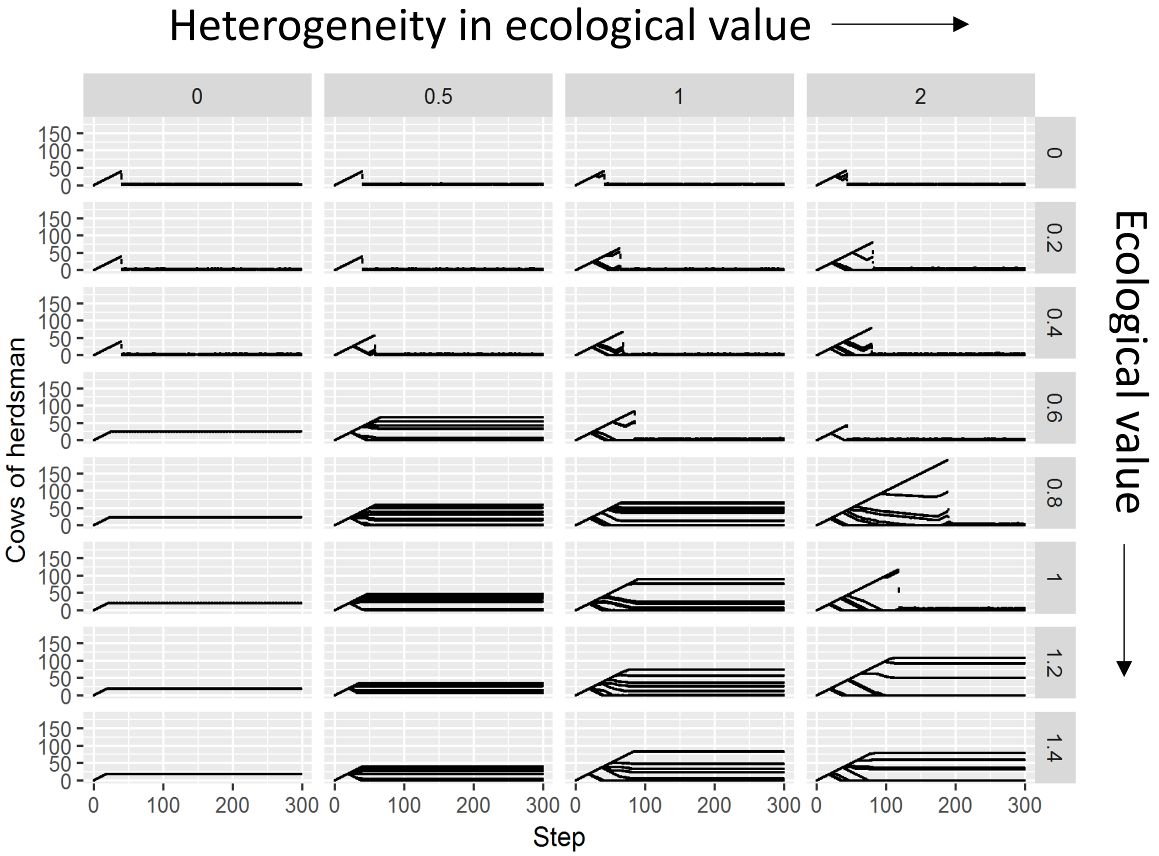


Figure 27: High heterogeneity in environmentalism increases probability of collapse.