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IMPACT OF DIVERSE BEHAVIORAL THEORIES ON ENVIRONMENTAL MANAGEMENT: EXPLORATIONS WITH DAISYWORLD

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ABSTRACT

Our understanding of human behavior is limited and consequently lacks a standard formal model of human behavior that could represent relevant behavior in social-ecological systems. In this paper we explore the consequences of alternative behavioral models using a simple dynamic system of agents of harvesting daisies in the well-known Daisyworld model. We explore the consequences of different behavioral assumptions and derive optimal tax policies that lead to sustainable outcomes for each of the theories.

1 INTRODUCTION

Human behavior in models of human-environmental systems is typically built on the mathematically oriented theories from rational choice (Clark 1976, Nordhaus 1994). However, social science has a broader and more diverse set of relevant (qualitative) behavioral theories. What is the sensitivity of projected human impact on the environment if we explore different representations of our understanding of our understanding of human behavior (Janssen and Jager 2000; Fulton et al. 2011; Milner-Gulland 2012; Schlüter et al. 2016).

Building on the framework of Schlüter et al. (2016) we use a stylized model of agents and its environment to explore the impact of different behavioral theories. We explore the consequences on the long term dynamics of the system, and evaluate how the optimal policies differ among the different behavioral theories. Besides rational choice and bounded rationality, we will implement descriptive norms (Bandura 1988), theory of planned behavior (Ajzen 1991) and habitual behavior (Pavlov 1927) (see also Schlüter et al. 2016).

Schlüter et al. (2016) reviewed the literature and provide a framework we implement the theories they selected as a representative spectrum of behavioral diversity. We sketch the main dynamics very briefly in this paragraph. When we describe the model formulation we will provide more specific details. **Rational choice** will evaluate all the possible decisions and selects the option that maximizes its expected utility. **Bounded rational** actors can be bounded in various ways, such as limited information or limited cognitive processing power. As a consequence the bounded rational actor may not find the optimal decision the rational actor did. Behavior that relies on **descriptive norms** assumes that actors will take into account the observed behavior of others to take their decisions, which include imitating behavior. The **theory of planned behavior** assumes actors define intentions based on behavioral control, social norms and personal preferences. But intended behavior may not be implemented since actors have no full control to realize their intentions. Finally, **habitual behavior** assumes that actors respond to rewards from past behavior, reinforcing positive experiences.

We make use of Daisyworld as a simple model of the biophysical system (Watson and Lovelock 1983). In Daisyworld there is only one life form, namely daisies. Black daisies will reflect light and black daisies absorb light. Daisyworld receives radiant energy from the start around which Daisyworld is orbiting. The population of white and black daisies led to local cooling and heating effects due to the albedo effect of the color of the daisies covering the surface of Daisyworld. For a temperature of 22.5 degrees Celsius the reproduction of daisies is maximal, but with lower and higher temperatures the reproduction rates decline. When we introduce agents who are collecting daisies, it will impact the sensitive interaction between the biosphere and the climate system. We will explore how different assumptions of behavior affect the outcomes, and what will be appropriate policies for the different behavioral theories.

This exercise will illustrate the challenges of implementing diverse behavioral theories for a simple social-ecological system, and how this could impact the outcomes for policy analysis. A key challenge is that most theories can be implemented in many different ways and our analysis will therefore never be complete. In the next section we will discuss the model in more detail. We will subsequently present the consequences of agents acting according to alternative behavioral theories on the social-ecological system, as well as the effectiveness of a daisy tax to reduce the harvesting of white daisies. The paper concludes with a discussion of the consequences of the findings.

2 MODEL DESCRIPTION

2.1 Daisyworld

The model used in this study extends the Daisyworld model by including agents who consume daisies. Daisyworld was originally developed to illustrate the Gaia hypothesis, the climate as a self-regulated system because of the interactions with living organisms (Watson and Lovelock 1983). It assumes a world filled with black and white daisies. Those different types of daisies have different types of ecosystem services, since they differ in albedo (absorption of heat from sunlight). White daises have a local cooling effect while black daisies have a local heating effect. However, daisies can only reproduce within a certain temperature range.

We use the original Netlogo version of Daisyworld (Nowak and Wilensky 2006) and include harvester agents that move around and harvest daisies. We implement different behavioral theories, and evaluate the impact of those different theories. Moreover, we want to explore the consequences of different policies for those various theories to maintain the ecosystem services of the daisies. A detailed model description and code are available at https://www.openabm.org/model/4958/version/1/view.

The environment is a torus with patches not representing actual physical dimensions. The patches can have a white or black daisy or are open space. At most one daisy can be on a patch. Dependent on what is on the patch, the patch has an albedo affecting what percentage of the sunlight is absorbed. For simplicities sake we assume for this model a constant amount of sunlight. Then we can calculate the local-heating as

Local-heating = 72 * LN(1-albedo)) + 80

The albedo for the white daisy is 0.75, the black daisy is 0.25 and for open space is 0.4. Half of the heat spreads to neighboring patches, such that the local temperatures are influenced by land cover at neighboring cells. The global temperature is the mean of the local temperature of all the patches.

A daisy has a maximum lifespan of 25 time steps. A daisy can reproduce another daisy to a neighboring patch with the probability P_r which is defined as

$$P_r = 0.1457 \cdot T - 0.0032 \cdot T^2 - 0.6443$$

The optimal temperature is around 22.5 ºC on that patch. If the temperature is higher or lower there is a lower probability of reproduction. If the temperature on a patch is lower than 5 ºC or higher than 40 ºC there is no reproduction possible. With the settings above the Daisyworld maintains a temperature around the optimal level with both black and white daisies populating the patches. One can imagine that a reduction of one color type of daisies may affect the feedback between the living organisms and the climate.

Each time step each agent will make decisions on movement and harvesting and execute those decisions. For each agent the utility is calculated. In line with basic economic theory we assume that agents receive utility from consuming white and black daisies, and from having leisure. Although we will calculate utility, not all behavioral theories we distinguish will make use of utility values to make decisions.

Agents have stocks of accumulated white and black daisies (w_w and w_b) which decay with rates m_w and m_b, respectively (we assume 0.3 is the default case for both). Agents value their time and spend time for moving to other patches and harvesting daisies. The utility of the agent is defined by the following classic Cobb-Douglass function capturing the tradeoff between material wealth and leisure.

$$U = (\alpha w_b + \beta w_w)^{\gamma}(1 - L)^{1-\gamma}$$

Where L is the fraction of labor spend in movement and harvesting, and α and β the relative utilities for a unit of black or white daisies. The elasticity parameter γ defines how wealth versus leisure is valued.

Table 1: Overview of the parameters used in the model including their default value.

Parameter	Meaning	Default value
Γ	Elasticity	0.5
α, β	Weights for black and white daisies in utility function	1
m_b, m_w	Decay rates of the stock of daisies	0.3
L_m	Labor time spend to move	0.25
L_b, L_w	Labor time spend to consume a black or a white daisy	0.2
R	Radius of patches in which agents compare themselves	4
p_r	Probability of reproduction	0.001

Agents can reproduce and die. They reproduce with probability p_r if the utility is beyond U_{min}, while they die if utility gets down to zero. When an agent produces offspring, the stock of daisies is shared equally between the parent and the child.

We implemented the five different theories as described below. It is important to realize that although we implement a certain theory, we had to make specific interpretations and assumptions for the implementation. As such the results are illustrative and may change for alternative implementations of the theories (see Schlüter et al. 2016 for a broader discussion of the theories implemented).

2.2 Rational Choice Theory

There are a number of simplifying assumptions made for implementing the rational choice theory. We assume that agents have perfect local knowledge of the temperature and daisies on the own patch and the eight surrounding patches. Agents maximize their utility for the current time step. They evaluate the four possible situations, select the one with maximum utility and execute the decision they have made. The order in which agents make their decisions is random, and is randomized again the next time step. The four possible behavioral options are:

- Don't move and don't harvest
- Don't move and harvest
- Move and harvest white daisy
- Move and harvest black daisy

The option Move and don't harvest has by definition a lower utility compared to Don't move and don't harvest. A consequence of this is that an agent in a depleted area will not move, although in the long term it would be beneficial to move and reach again areas with daisies. This is a possible adjustment of the rational actor which takes into account the future returns. At the moment a rational actor is assumed to enjoy their leisure if the local area is depleted.

In doing this exercise one realizes that a pure rational actor approach is difficult to achieve in agent-based models. Ideally one would include agents with perfect information about the actions of others and resources available. Would one move two patches for a white daisy to maximize the expected discounted utility instead of move to the other patch for a black patch? This requires knowledge on whether the white daisy is still available when the agents can make a decision in the next time step. In an analytical model one may approximate such equilibrium but a spatially explicit model of independent actors makes such rationality next to impossible. Therefore we simply assume rational choice of the locally available information.

2.3 Bounded Rationality

We implement bounded rationality by satisfying agents. Agents will only put in effort to explore all options if they are not satisfied. Since we assume that agents make decisions based on the options directly available to them (and not the long term consequences of their actions), this seems to be a reasonably variation of bounded rationality. In the default setting, we assume that the threshold of utility for which agents are unhappy is the same as the threshold for which agents will have a probability to reproduce.
If the agent is satisfied it stays at the location. If not satisfied it will consume the daisy if a daisy is present on the patch. If there is no daisy at the patch, it will move to one of the neighboring patches with a daisy. If no neighboring patches has a daisy it will move to a random neighboring patch.

2.4 Descriptive Norm

Agents derive information about the choices made by others in a neighborhood of radius r. This will influence their decision. There are various ways this can be implemented. Will an agent using descriptive norm always imitate the dominant behavior observed or only in specific situations? We assume that agents will only imitate if they have a certain minimum level of utility. If agents are satisfied they perform the dominant choice if this option is available. They check whether there is a daisy of the dominant choice on the patch, consume that daisy. If there is not such an option go to a neighboring patch with a daisy of the dominant choice and consume. If that is not possible, go to one of the possible neighboring patches which are not occupied by another agent. If the agent is not satisfied, the agent consume the daisy on the patch if possible, or consumes a daisy at a neighboring patch if possible (not taking into account which color).

2.5 Habitual Behavior

Habitual behavior is implementing as agents who initially do not know the consequences of their actions and explore their behavior. Like pigeons learning which levers lead to appropriation of food. Agents take decisions and learn the reward from those actions. This will reinforce certain actions. We implement habitual behavior thus as a reinforcement learning process.

We assume that agent can choose between five options, the four considered in the rational choice implementation, and moving to an empty neighboring patch. This last option was not considered in the rational choice option since it will never be the rational option to choose if one maximizes the utility of the current time step. Initially the agents do not know the expected value of those five options, which they learn through exploration of the environment. Initially, all the propensities q have equal values, say 1. When an agent derives information from a decision that is made, it will update the propensities in the following way:

$$q_i(t)=q_i(t-1)*\eta + U(t-1) \text{ for the propensity of the choose that is executed}$$

and

$$q_i(t)=q_i(t-1)*\eta \text{ for the other behavioral options}$$

where η is the fraction of the propensity that is carried on to the next time step, a kind of memory. This means that propensities only can increase for options that are chosen. The propensities are used to make a probabilistic choice. The probability of choosing propensity i is equal to $q_i / \Sigma_j q_j$. Hence the higher the value of a propensity of choice i relative to other options the higher the probability this option is chosen. Thus habitual behavior could appear where agents keep repeating the same decisions and not getting relevant info on the real values of the other options.

2.6 Theory of Planned Behavior

For this theory implementation we first calculate the intentions agents have, and then check whether the intended behaviors can be implemented. The intention is based on personal attitude, social norm and behavioral control. We assume that personal attitude is based on the utility an agent derives from consuming a white or a black daisy. This is implemented by assuming a value α for the black daisies and a value β for the white daisies. The subjective norm is the dominant choice in the previous time step of the agents within a radius r.

Behavioral control relates to the distance between the harvesting agent and the target daisy. More precisely, we use the equation $1/(1+d)$ where d is the distance. Hence a daisy on the current patch has a behavioral control value 1, while a daisy two steps from the current position has a behavioral control value 1/3.

For each daisy in a radius r the intention value is calculated using the equation

$$I = w_{pa} * \text{attitude} + w_{sn} * \text{Norm} + w_{bc} * 1/(1+d)$$

If the maximum intention value is above w_{bc}, the agent will use that daisy as a target of intended harvesting (where d is the distance of the agent to the daisy).

After all the intended behaviors are calculated, we calculate the actual behavior. An agent can only move to a patch that is not yet occupied by another agent and thus it is possible that the intended behavior cannot be implemented. In fact one daisy could have been a target of various other harvesters and snatched away before the agent could implement it’s intended behavior.

3 RESULTS

3.1 Base Case

Our analysis starts with an exploration of the rational choice agent. Figure 1 shows the outcome distributions for 100 simulation runs. The model initially experiences a rapid increase of the population due to large availability of daisies. When the daisy population starts to decline (overharvesting) the population levels start to decline not much after the peak of daisies on the landscape. This is the common Lotka-Volterra cycle. In most cases the daisies get depleted and this will be the end of the agent populations. When there is a low population of daisies the global temperature also raises leading to a smaller reproduction rate of the daisies.

In some cases sufficient white daisies survive that enable the population to recover. With agents that harvest daisies, there is not much ecosystem service for the black daisies (in fact we can see it as a weed using up space and increasing the temperature).

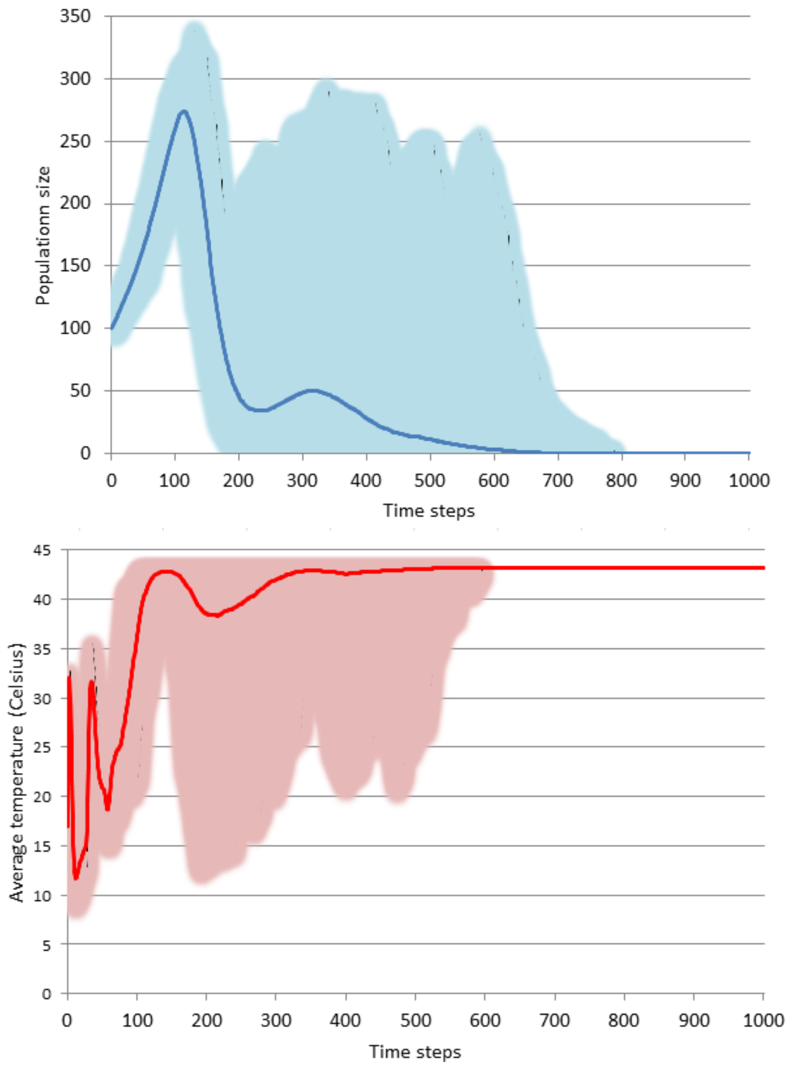

Figure 1: Average outcomes of 100 runs. Top figure is the population size of daisy harvesters, and the bottom figure is the global temperature. We also project the spread of the trajectories by coloring the area minimum and maximum observed values.

In the Figure 2 the results are presented of the averages of 100 runs and show the diversity of outcomes among the different behavioral models. When agents are habitual they are able to sustain a high population level. Those agents enjoy their leisure and do not always collect a daisy if this is possible. They also sometimes move randomly around (which still will give them utility). Bounded rationality also leads to a sustainable population, but at a lower level. Those agents aim for a minimum utility level 2, and because of their focus on collecting daisies to increase their utility, this lead to an initial overshoot and decline.

The descriptive norm leads to a rapid rise of the population since agents focus on harvesting agents, like other agents they observe. Since agents with descriptive norms are more likely to focus on harvesting daisies with the same color, this leads to temperatures that are outside the domain of high reproduction of the daisies. Therefore we see a faster rise and fall of the population.

Agents who make decisions according to the theory of planned behavior, balance their preferences and observed dominant behavior. This lead to behavior similar to the rational actor. Also the agents have no perfect behavioral control, they typically execute decisions they intend to do.

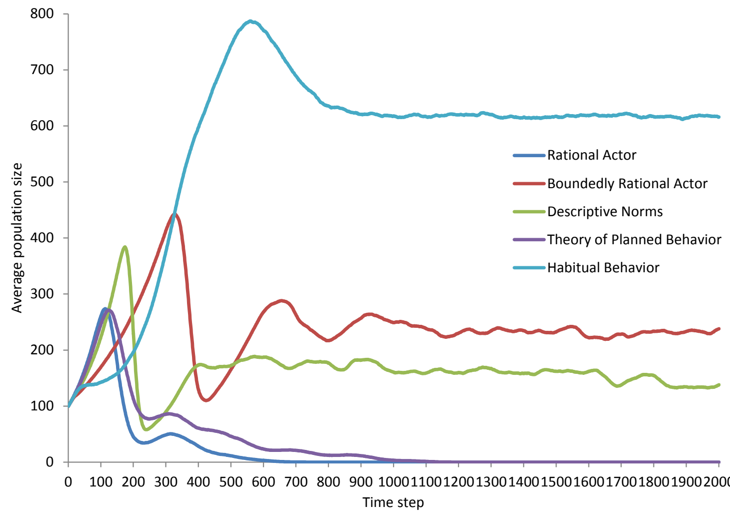

Figure 2a. The average population levels of daisy harvesters for 100 runs of each of the 5 behavioral theories.

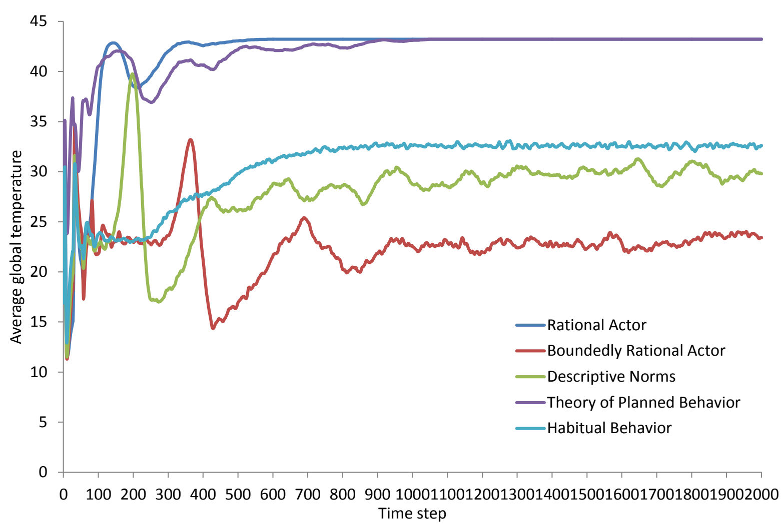

Figure 2b. The average global temperature for each of the 5 behavioral theories.

3.2 Tax Policy

We do now include a tax policy on daisies. Since white daisies have a cooling effect, harvesting white daisies has a damaging impact to destabilize the climate system. Tax is the fraction of the harvested white daisy that is not added to the stock of the agents. Hence if tax is 1 (=100%), agents will not receive any return from harvesting white daisies. Figure 3 shows the population size after 1000 time steps (average between 1001 and 2000 time steps) for the different theories and different levels of tax. The rational choice agents benefit if there would be a tax implemented around 0.45. Except for the Habitual Behavior, which has already a sustainable behavior without a tax, all theories benefit from having a tax policy. However, the optimal tax policy differs among the theories. Evaluating the impact of the daisy tax for population size, utility and temperature, it seems that a tax between 0.4 and 0.5 does avoid the most negative outcomes if not being correct on the underlying behavioral theory.

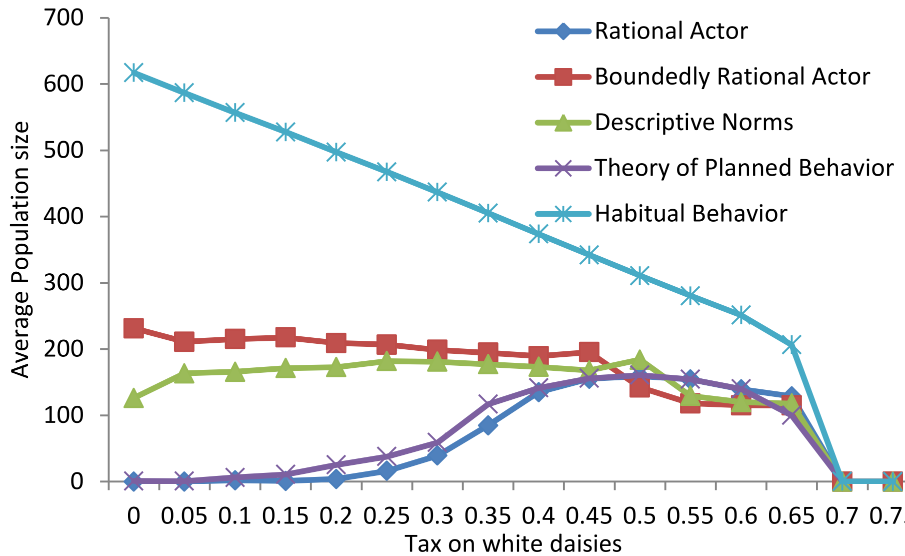

Figure 3a. Average population size of daisy harvesters for different tax levels for each behavioral theory.

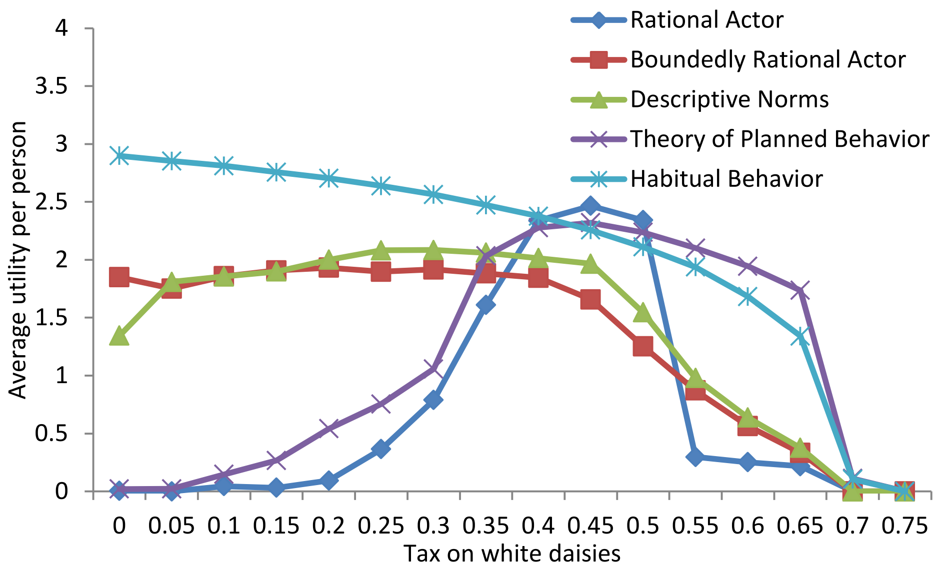

Figure 3b. Average utility per person for different tax levels for each behavioral theory.

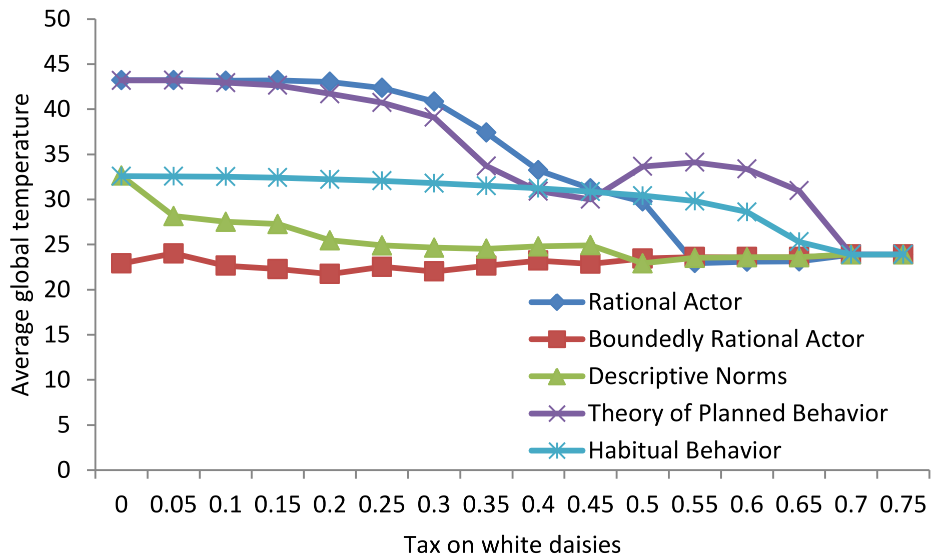

Figure 3c: Average global temperature for different tax levels for each behavioral theory.

In Table 2 we compare the optimal policy for agents behaving according to theory A and evaluate how this will impact agents behaving according to theory B. We can now evaluate which policy is the most robust. Since the utility for models with rational actors and agents who make decisions according to the theory of planned behavior are most sensitive to different tax values, one could argue that a policy according to the rational actor would be an appropriate decisions (assuming the size of the different sub populations are similar). Of course, additional sensitivity analysis could be done to evaluate the robustness to specific assumptions of implementing behavioral theories, as well as assumptions on the preferences of the agents (including heterogeneity).

Table 2: Average utility values per agent after 1000 time steps for different policies and behavioral models.

Policy\model	Rational Choice	Bounded Rationality	Descriptive Norms	Theory of Planned Behavior	Habitual Behavior
Rational Choice (0.45)	2.47	1.66	1.97	2.32	2.26
Bounded Rationality (0.2)	0.09	1.83	2.00	0.54	2.70
Descriptive Norm (0.3)	0.79	1.92	2.08	1.06	2.56
Theory of Planned Behavior (0.45)	2.47	1.66	1.97	2.32	2.26
Habitual Behavior (0)	0.00	1.85	1.34	0.02	2.90

3.3 Heterogeneous Populations

In the next experiment, we start with 20 agents of each behavioral theory, and evaluate whether we get different results with a mixed strategy. Since agents modeled according to different theories will make decisions that lead to different utility levels, this will impact the demographics and therefore the distribution of the theories represented by the agents in the population. Basically, the population size is dynamic and reproduction rate and death depends on the utility levels of the agents. Which theories will dominate? Without any tax policy we experience that no agents will survive after 1000 time steps. Although some behavioral theories would lead to a sustainable outcome, the agents who make decisions according to rational choice, descriptive norms and theory of planned behavior dominate and cause the system to collapse.

When we include a daisy tax we see that for low tax levels, the rational actor dominates, and for higher tax levels, we observe a larger share of agents who make decisions according to the theory of planned behavior. Although agents according to habitual behavior and bounded rationality lead to more sustainable outcomes, a dynamic mix will experience a dominance of the short term utility maximizing agents. As a consequence to optimal tax will be similar as the rational choice scenario, namely 0.45.

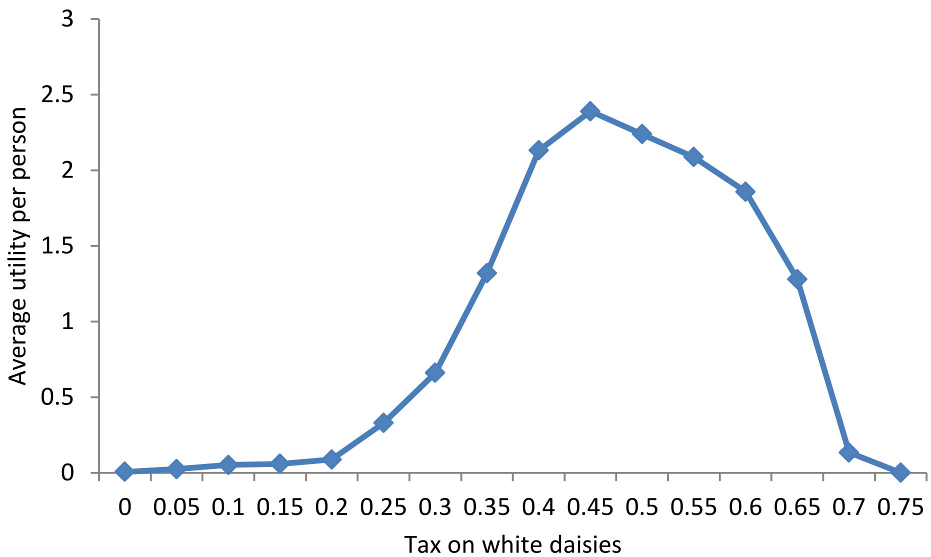

Figure 4a. Average utility for last 1000 time steps for different tax levels when population has diverse behavioral rules.

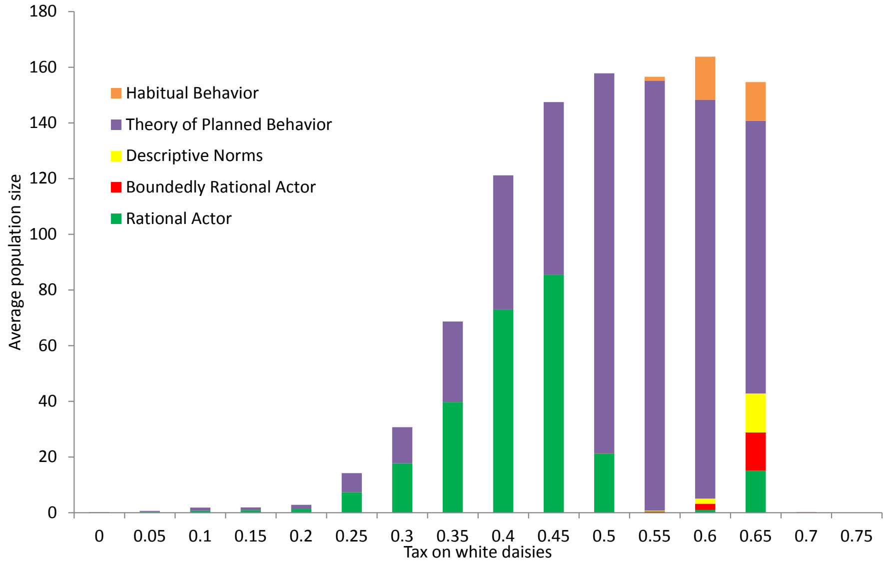

Figure 4b. Distribution of behavioral theories among the daisy harvesters for different tax levels.

4 CONCLUSIONS

In this paper we explored the consequences of alternative representations of human behavior in a simple social-ecological system. Using Daisy World we included agents who make decisions according to various behavioral theories from the behavioral sciences. Some behavioral theories lead to sustainable outcomes, such as habitual behavior and bounded rationality. Other behavioral theories such as rational choice, descriptive norms and the theory of planned behavior are maximizing expected outcomes and this lead to overshoot and collapse of the daisy population.

We explored the consequences of a daisy tax and find different optimal values for the various behavioral theories. In this particular system a daisy tax calculated for rational choice operating agents is a level that leads to overall good outcomes for models according to alternative theories.

The main conclusion from this exercise is not the specific results, but the observation that the implementation of behavioral theories depends on many assumptions. To implement a theory in a particular context require interpreting the intended behavior and implicit assumptions of the particular theory. In fact each theory has to be adjusted to an application and therefore it will be difficult to make generalizable statements on the implications of behavioral theories. However, our analysis also shows the importance of performing sensitivity analysis for alternative behavioral theories.

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