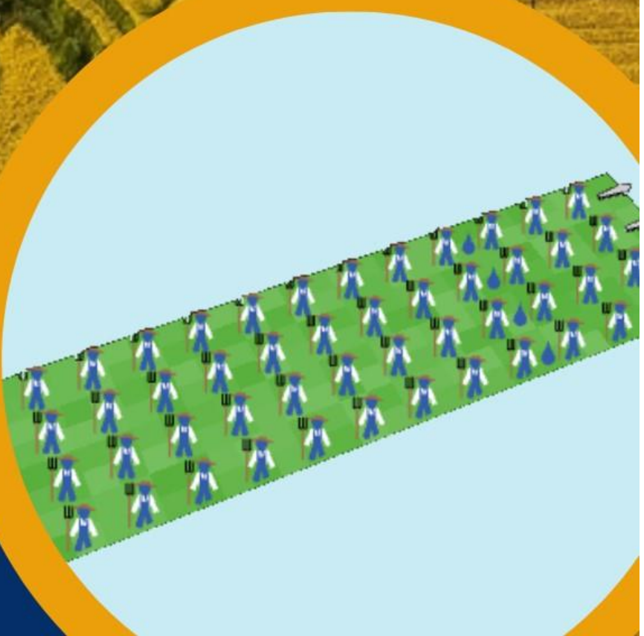
MASTER'S THESIS – SUSTAINABLE DEVELOPMENT
UNIVERSITY OF UTRECHT

Self-Organizing Institutions for Mobile Common-Pool Resource Units: An Agent-Based Model



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Content

Acknowledgments

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Summery

Irrigation systems are the life line of many agricultural communities and farmers, and may be common pool resources (CPRs). CPRs are characterised by non-excludability and subtractability. However, irrigation systems are also characterised by the mobile nature of the CPR units: the flow of water. Wrongful management of CPR can result in the depletion of the system, and suffering for the farmers. Scientific literature argues that CPRs can be managed through institutions, preferably self-organising institutions. The formation of these institutions is complex, and no single research method provides a complete understanding of the conditions that foster successful institutions. Through the use of agent-based models (ABM), a deeper understanding of the fundamental workings of this process can be achieved. ABM is particularly useful as a bridge between mathematical/economic equations, and social observations. However, existing ABMs covering the formation of institutions focus on stationary CPR units. No ABMs explore the formation of institutions under the assumption of mobile CPR units.

Focussing on irrigation systems, this thesis describes under which conditions institutions emerge and how they perform. Previous literature on stationary CPR units suggests that stable institutions are crucial for the success of institutions. This thesis asks, *how does the mobility of the common-pool resource units affect the formation and success of stable institutions in an agent-based model?*

To answer this question, I have designed an ABM heavily based on the combination of the existing ABM by Ghorbani et al. (2017) and the irrigation dilemma by Janssen et al. (2011). In this model, the farmers have to balance their extraction and contribution to maintain the irrigation system. In addition, they can vote on an institution and its design, which limits the farmers extraction and forces contribution. The variables that describe the farmers, the irrigation system, and the collective-choice rules are correlated to the stability of the institution. Additionally, the success of the institutions is measured in terms of CPR sustainability, user welfare, and fairness.

It was found that stable institutions result in more successful outcomes. Resource availability seemed to play a central role formation of institutions. As an important difference with immobile CPR units, this ABM showed that an increase of power to a (repressed) minority results in more stable and successful institutions.

This thesis seeks new insights in the formation of institutions. At the same time, this novel ABM can act as a gateway to more applied research opportunities and policy applications.

Keywords: Endogenous institutions, Agent-based model, Common pool resources, Mobile resources.

1. Introduction

Depletion of common pool resources (CPR) is a risk many socio-ecological systems (SES) face when actors are not cooperating in an effective manner (Ostrom, 2009). CPR are defined as non-excludable and subtractable (Ostrom et al., 1994). This means that it is difficult to exclude those that did not contribute from using the resource, and that once captured and used, the resource unit is not longer available for others. Certain forests, fisheries, and irrigation systems are prominent examples of CPR. In addition, CO2-emissions, air-, ocean- and river pollution also resemble aspects of CPR characteristics (Dolšak & Ostrom, 2003). It is crucial to understand how to manage CPR effectively to promote sustainable practices and to ensure the long-term viability of these shared resources (Ostrom et al., 1999).

Due to the non-excludable and subtractable nature of CPR, any individual user has the capacity to contribute to their depletion. Traditional economic theory predicts, under the assumption that each individual acts solely to maximize their own profit, that CPR are prone to overexploitation and underinvestment (Hardin, 1968). This scenario, often referred to as the "tragedy of the commons", ultimately leads to the collapse of the SES that relies on the CPR.

Ostrom showed that collective action is the key to successful CPR management (Ostrom, 1990). Collective action relies on the existence of institutions, defined as “the sets of working rules that are used to determine who is eligible to make decisions in some arena, what actions are allowed or constrained, what aggregation rules are used, what procedures must be followed, what information must or must not be provided, and what payoffs are assigned to individuals dependent on their actions” (Ostrom, 1990. p51). In this paper, *successful* institutions are defined as institutions that lead to sustainable use: sufficient and fair extraction for the users, and protection from depletion for the CPR (Agrawal, 2001. p1650). The formation of successful institutions is complex, and each SES requires a different (arrangement of) institution(s). There is no “panaceas” (a single simple solution that solves everything) (Ostrom, 2007), making the study to the formation of sustainable institutions equally complicated.

The analysis of the formation of institutions should be done from multiple different viewpoints to capture its full complexity (Poteete et al., 2010). Case studies provide insight on factors in specific contexts influencing the success or failure of institutions (see, e.g., Ostrom & Gardner, 1993; Sarker & Itoh, 2001; Heikkila & Gerlak, 2005). However, the focus on the contextual factors in unique situations makes generalisation of conclusions difficult. Controlled experiments address this by isolating factors like the quality and quantity of CPR, and social characteristics of the users in field or lab (Anderies et al., 2013; Baggio et al., 2015), but these experiments also have limitations. Their small scale and time intensive set-up restrict the study of the long term -sometimes decades- formation of institutions, and rely on natural experiments for which longitudinal data. However, restricted data availability limits this kind of research.

Poteete et al. (2010) advocates for a complementary research method: Agent-Based Modelling (ABM). ABM is the digital study of complex emerging patterns based on the behaviour of individual agents. These computer-generated models can test and compare multiple scenarios of the same system, eliminating the contextual differences of case studies. Furthermore, ABM allows to explore scenarios that traditional experimental studies struggle with due to long-term setup requirements, high costs, ethical concerns, or the impossibility of testing them on real humans. In short, ABM could contribute to identify which conditions promote the formation of successful institutions (Poteete et al., 2010).

The leading ABM on the formation of institutions is the model by Ghorbani et al. (2017). They found that the stability of the institution itself is of high importance in the success of the system. Stable institutions are defined as rule systems that do not change even if the users have the possibility to (Ghorbani et al., 2017. p33). They found that stable institutions are associated with higher resource availability and greater user well-being. Essentially, stable institutions were found to be successful institutions.

The current ABMs covering the formation of institutions exclusively focus on CPR such as forests or pastures. The CPR units in these systems, wood or grass, are immobile. Schlager et al. (1994) showed that the mobility of the CPR unit is a defining factor in the kind of institutions that are formed. Mobile resources introduce uncertainty about the position, quantity, and quality of the CPR. This uncertainty increases the interdependency among users, and complicates the formation of successful institutions. The difference between the types of institutions needed for mobile and immobile CPR units, restricts the generalisation of the conclusion from one to the other. Therefore, for a complete understanding of the formation of successful institutions, ABM should also cover mobile CPR units in the study to stable institutions. The observed research gap resulted in the following research question:

How does the mobility of the common-pool resource units affect the formation and success of stable institutions in an agent-based model?

This information is relevant in three ways. First, current policies that design institutions for the use of mobile CPR units are based scientific insights based on stationary CPR units. If Schlager et al. (1994) is correct in their conclusion that mobile CPR units require different institutions, many policies are based on the wrong assumption, and should be based on these updated insights. Secondly, this paper presents a unique model of institutional emergence combined with mobile CPR units. This new model can form the basis for many different applied cases. As illustration, the ABMs used for immobile CPR units by Ghorbani et al. (2017) is used for applied cases ranging from electric grid design (Acosta et al., 2018) to communal garden management (Feinberg et al., 2021). The same diverse results can be expected from this model. Lastly, this paper contributes to the goal to study institutions in a varied manner described by Poteete et al. (2010) by taking another angle in account. The complexity of CPR management is never fully understood, but the multitude of viewpoints can bring us closer.

The structure of this paper is as follows: in chapter 2, I provide more background on the method of ABM, relevant ABM studies, and expand on the concept of mobile CPR units. Chapter 3 explains the design and its use of the ABM in this paper. In chapter 4, I present the results of the ABM, which I interpret and discuss in chapter 5. Finally, I conclude this paper with the key findings and their significance in chapter 6.

2. Background

This chapter provides information on ABM methodology to give insight into the possibilities and limitations of this method. In addition, it discusses existing ABMs covering the formation of institutions, and dives into the most prominent study that is used as basis for this paper. Hereafter, ABMs and other studies covering mobile CPR units are presenting to further specify the definition and impact of the mobility of CPR units. This chapter ends with a suggestion to merge the discussed prominent study with mobile CPR units in a single ABM.

2.1 Methodology of ABM

ABM is a method to examine complex systems and emerging patterns. It allows to simulate individual decision-making processes and explore the resulting behaviour of that system. ABM is especially useful in non-linear systems involving adaptation or learning, or when modelling complex social interactions. SES are heavily dependant on the actions of individuals and often complex, making ABM a good research method for these systems (Elliott & Kiel, 2004).

Designing an ABM involves translating the essence of a system into a set of assumptions. These assumptions are then coded into an algorithm. The level of detail within these assumptions, and consequently the code itself, determines the type of insights the ABM can generate. General and abstract assumptions result in generalizable conclusions about the workings of the system. On the other hand, many and detailed assumptions, fed with geo-spatial or historical data, can be used for more applied purposes. In both cases, ABM has the capacity to form the bridge between purely mathematical models and the complexity of real-world social observations .

While ABM is a useful tool to study complex systems, it also has some limitations. The full complexity of reality, especially when human emotions, errors, and creativity is modelled, is very hard to capture in a model. Therefore, precise numerical outcomes of an ABM should be treated cautiously, and even more cautiously when the abstraction of the ABM increases. It is often more useful to use ABM to gain a deeper understanding of the system's mechanisms than to find exact answers. The deepened understanding can then be the foundation for new policies.

2.2 ABM of institutional emergence

Previously, ABMs have provided insight in the factors that impact the emergence of institution. Smajgl et al. (2008) showed how endogenous rule change happens in a social groups, revealing critical steps in rule-changing processes. Pitt et al. (2012) expanded the way computer scientist could model collective action and institutions by formalizing the design principles of Ostrom (1990). Chen et al. (2012) used ABM to identify the role of social factors of the agents on willingness to contribute and be part of an institution. They found that interactions, social norms, and communication would enhance the enrolment of the users on theses institutions by reproducing a current agricultural situation. This shows that more and more complex human behaviour could be captured in an ABM. Perry et al. (2018) expanded on this by simulating collective action in heterogeneous groups that could punish and adapt to punishments. This is significant because this would address the problem that it is increasingly difficult to model strategy adaptation to other-agent-referencing ideas in an ABM. All these ABMs studying the formation of institutions do not yet place these institutions in the context of CPR. The work of Bravo (2011) shows that in simple and abstract CPR management problems, endogenous institutions improve the system’s overall working, mimicking bottom-up rule emergence between people.

2.3 ABM of institutions for immobile CPR units

Expanded on the model of Bravo (2011), Ghorbani et al. (2017) present an ABM focused on identifying the conditions that promote the emergence and success of institutions for immobile CPR units. They claim that the stability of institutions is crucial for the institutional success and sustainability. Their research further identify specific conditions of the users, institutions, and environment that promote this stability. The model's function is aligned close to the desired goal of this paper. Therefore, their model serves as a strong foundation for this paper, and deserves a closer examination.

2.3.1 Overview

Ghorbani et al. (2017)[1] model a CPR management scenario where agents extract a shared, immobile resource (representing, for example, a shared forest). Each agent has an individual strategy telling them when and how much of the resource to extract. The model presents opportunities for the agents to establish an institution, defined as shared rules. However, this is only done if a majority of agents cannot extract sufficient resources. Once established, the institution dictates, instead of their personal strategy, when and how much resource to extract. The design of this institution is a bottom-up process. Each agent votes for its preferred strategy, and the strategy with the most votes becomes the enforced institution. The institution is not static. It can be altered again if a majority do not gain enough resources under the current institution. Unchanged institutions were deemed stable, while institutions that changed often were deemed unstable.

The stability the institution was the focus of the study. They found that stable institutions were correlated with a more successful management of the SES, where no overharvesting of the CPR or suffering of the agents took place. In stable scenario's, the farmers could extract just enough resources to prevent them from triggering a institutional reform. They also found that certain conditions resulted in more stable, and thus more successful, institutions. For example, they demonstrated the thin line of resource availability for the users where stable institutions emerged more often. However, other conditions, such as the share of farmers needed to gain a majority for institutional reform, did not have an significant impact on the stability or success of the institution.

2.3.2 Levels of institutions

The paper of Ghorbani et al. (2017) gives a fundamental insight in the way stable institutions form and perform. However, their paper does not explicitly distinguish between the different institutional levels, described by Kiser & Ostrom (1982). The analysis of institutions should keep these different levels in mind to avoid confusion. Kiser and Ostrom claim that an institutional arrangement, and study thereof, can be divided into three levels: the operating rules, the collective-choice rules, and the constitutional rules.

- **The operational rules** dictate the everyday choices actors make**.** In the model of Ghorbani et al. (2017), these represent the core institutions of interest. The focus lies on the rules governing the resource extraction by the agents. The ABM investigates the stability of these rules and impact on overall performance.
- **Collective-choice rules** govern the process of creating and modifying operational rules. These rules determine who can participate in discussions about operational rules, how often these discussions occur, and the procedures for making changes. In the ABM of Ghorbani et al. (2017), the collective-choice rules are pre-programmed by the model designers. The agents have no influence on them. When the study identifies specific institutional conditions (e.g.,

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[1] This model is the centre of a series of papers. The first mention of this ABM is Ghorbani & Bravo (2016)

time between voting rounds, majority thresholds) promoting (operational) institutional stability, these conditions are on the collective-choice level.
- **Constitutional rules** define the framework for designing and modifying collective-choice rules. While this level might be relevant for real-world institutional analysis, it becomes less applicable in the ABM of Ghorbani et al. (2017)[2].

When analysing institutional arrangement, precise terminology is important to prevent confusion. Ghorbani et al. (2017) demonstrate this challenge by using "institution" to refer to both the operational rules and the collective-choice rules, which makes the interpretation of ‘stable institutions’ potentially ambiguous. To clarify: the collective-choice rules are (one of) the independent variables, and are always stable within a single model run. The operational rules are the dependant variable, and are not always stable within a run, which is exactly the interest of the study: when are the operational institutions stable? In addition to more clarity about the concepts, adopting a common vocabulary for the analysis of institutions by ABMs facilitates the transfer of knowledge to other scientific disciplines.

2.4 ABM of institutions for mobile CPR units

Ghorbani et al. (2017) identified the conditions promoting the emergence stable institutions in their ABM study, but these findings were limited to the context of immobile CPR units. Currently, there are no ABM exploring the formation and success of operational institutions when dealing with mobile CPR units, making further research specifically focused on this type of CPR units necessary.

As defined by Schlager et al. (1994), mobile CPR units are those that can move independently of user activity. The mobility (or lack thereof) impacts the form and success of operational institutions governing their use. Schlager et al. (1994) identify various examples of mobile CPR units, including (some form of) fisheries and irrigation canals. To address the current gap in ABM research, a logical first step would be to focus on one of the these mobile CPR examples. Effective management of irrigation systems is a crucial concern for stable food production across the globe, and was chosen as the focus of this paper. However, not every irrigation system is the same, and an abstract form of irrigation systems that covers multiple irrigation is potentially the most valuable. To guide the development of an sufficient ABM covering this abstract irrigation system, it is worthwhile to examine existing ABMs that explore irrigation management.

Irrigation system ABMs employing specific historical, geographical, or specialized data are well-documented in the literature (see, e.g., Schlüter & Pahl-Wostl, 2007; Wise & Crooks, 2012; Okura et al., 2022). However, the aim of this paper is to achieve a general understanding of the mechanisms driving institutional formation within the context of mobile CPR units. Therefore, this paper does not use an existing ABM with highly specific data as a foundation.

Existing abstract ABMs on irrigation systems can provide valuable insights. For instance, Lang and Ertsen (2022) explored the interactions between farmers, irrigation systems, and environmental factors. Their work resulted in a general ABM for irrigation systems, offering insights into the effects of irrigation flow and harvesting patterns on the yield. Similarly, Cai and Xiong (2017) used an abstract ABM to demonstrate the critical role of government support in fostering inter-agent cooperation among farmers, and highlighting the role of the most dominant farmer in a system. Furthermore, Woldeyohanes et al. (2021) conducted a systematic review of ABMs exploring the opposite of

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[2] If it would be analysed, the study could potentially involve the rules governing the discussions among the model designers themselves. However, this level holds limited practical significance within the context of the ABM.

collaboration and shared rules: the emergence of non-cooperation among farmers. These studies collectively illustrate the potential of abstract ABMs to model complex human interactions within irrigation systems.

Many irrigation system ABMs are based on the irrigation dilemma, a variant of the CPR dilemma (Ostrom & Gardner, 1993b; Janssen et al., 2011). The irrigation dilemma highlights the inherent conflict within CPR management whenever the actors have unequal access to the resource. This dilemma presents a scenario where farmers positioned along a canal, face a conflict between individual extraction, and collective investment. The irrigation dilemma (Janssen et al., 2011) functions in the following way.

A canal-based irrigation system feeds water to a community of farmers. Strict hierarchy dictates water access: the first farmer (head-ender) has first access to the water, followed by the second, third, and so on, until the last farmer (tail-ender) can extract whatever water remains. Farmers can freely extract water. However, the irrigation system produces only so much water, and water used by head-enders is unavailable to those downstream. This extracted water is used for personal profit on individual farms, so every farmer is motivated to extract as much as possible.

However, maintaining optimal water flow requires maintenance. This maintenance is expensive. A collective tax on all farmers is the only way to finance this maintenance. The head-enders, lacking sufficient resources on their own, rely on contributions from the tail-enders. However, and this forms the heart of the dilemma, the tail-enders are unlikely to contribute to a system that gives them no benefit. So the head-enders have to leave enough water in the system to ensure the willingness for tax by the tail-enders. The head-enders have to resist the temptation to overexploit the system.

The frequent use and abstract nature of the irrigation dilemma makes it an ideal representation of an irrigation system to base the ABM covering mobile CPR units on. So, as a summary of this chapter: there is a research gap in the study to which conditions leads to the formation of successful operational institutions for mobile CPR units. A productive start to fill this gap is made by merging elements of the ABM of Ghorbani et al. (2017) and the irrigation dilemma by Janssen et al. (2011).

3. Model design

This paper presents an ABM that merges the self-emerging operational institutions and its analysis from Ghorbani et al. (2017) and structured extraction order and maintenance scheme from Janssen et al. (2011). This ABM investigates under which conditions stable operational institutions governing mobile CPR units emerge and if they are successful. The chapter starts with a short overview that describes the global workings of this ABM. The overview serves to contextualize the detailed and technical descriptions of each model element, presented in the second section. The chapter concludes by outlining how the ABM is utilized, calibrated, and analysed.

3.1 Overview ABM

The ABM simulates an abstract irrigation system with farmers situated along a single canal (see Figure 1). The water, represented as a single blue drop, flows through the canal from left to right (head-enders to tail-enders) each irrigation cycle. Farmers can extract water when it reaches their location. The water continues to flow downstream until depleted or until all farmers have extracted. After each irrigation cycle, farmers contribute a portion of their wealth as tax towards the collective system maintenance. A better funded system yields more water in the next irrigation cycle. Periodically, the farmers can vote to establish or modify an operational institution if a threshold of farmers are unhappy with the current situation. These operational rules dictate the height of water extraction and tax contributions for each farmer. I assume that one unit of water produces one unit of welfare for the farmer (hereafter referred to as the farmer's energy). And one unit of welfare is expended to pay for one unit of tax. Therefore, the water, energy and tax units are the same.

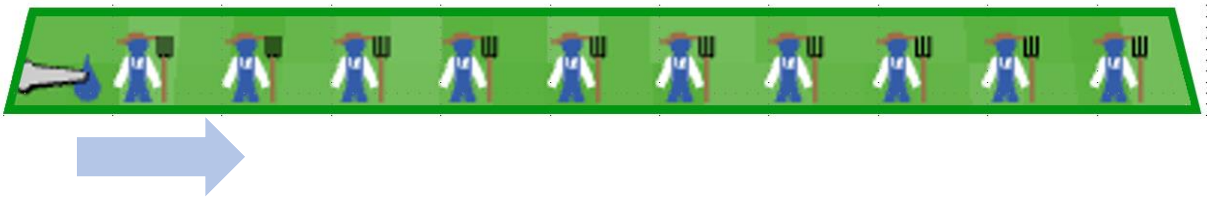

Fig. 1. *Schematic representation of the farmers and irrigation system in the ABM. The arrow indicates the flow direction of water.*

3.2 Model elements

The elements in this ABM are sorted along attributes of the people (farmers), attributes of the physical environment (irrigation system), and attributes of the rules-in-us (institutions) based on the IAD framework (Ostrom et al., 1994).

3.2.1 Farmers

The farmers are the agents in the ABM, and are described by their energy level, position along the canal, actions, and the farmer parameters.

1) *Energy:* The energy of the farmers represents their wealth and thereby their well-being. It goes up when the farmers extract water, to simulate increased farm production. It goes down when they pay tax. Additionally, it also goes down passively to represent the cost of living. At the start of each model run, the energy level is 100, and it is limited (to 200) to represent the maximal production of their farmland.
2) *Position:* Farmers are positioned along a single line, representing their location from the head-end to the tail-end of the irrigation system. These positions are fixed, and reflect the immobility of farmlands within the system.

3) *Actions:* The possible actions for the farmers are extracting, investing, and changing their extraction/investing tactic, based on the ABM of Ghorbani et al. (2017). The farmers extract and invest according to their personal tactic:
   - Extraction tactic: The farmer extracts X units of resources when Y condition is met.
   - Investment tactic: The farmer invests Z units of resources if they have sufficient energy

   The list of the amounts of resources (X and Z) and the list of the different conditions (Y) is given in table X. At the start of the model, each farmer is randomly assigned a combination of X, Y, and Z. During the model run, the farmers change their tactic if the farmer's energy level is below a certain threshold. This is done in two ways: to copy the X, Y, and Z of the farmer in their neighbourhood range with the highest energy-level (to simulate that farmers copy successful behaviour), or to be assigned with a random new combination of X, Y, and Z (to simulate innovation practices).

   Table 1. *Action variables and their values*

Action variable	Explanation	Variable options
X	Height of resource extraction	2<n<20 (steps of 2)
Y	The condition under which a farmer extracts	(ticks mod 5) = 0, (ticks mod 3) = 0, (ticks mod 2) = 0, always
Z	Height of tax	0<n<10 (step of 1)

4) *Farmer parameters*: Farmer parameters define the characteristics of the farmer population within a specific model run, and are (part of) the independent variables of this model. The five parameters hold constant values for all farmers during a single model run.
   - *Minimum energy*: the minimum energy level required for a farmer's well-being. Falling below this threshold triggers a change in their tactic.
   - *Energy use*: the cost of living that each farmer loses in energy each irrigation cycle.
   - *Neighbourhood range*: the number of farmers directly to the right and left of a farmer it considers when copying a more successful tactic.
   - *Innovation rate*: the chance the farmer who changes tactics picks the option to adopt a random new X, Y, Z combination. The reverse (1- innovation rate) is the chance to pick the option to copy the most successful neighbours' tactics.
   - *Number of farmers*: The number of farmers along the irrigation system.

3.2.2 Irrigation system

The irrigation system is the environment in which the farmers are simulated. It produces a single water 'wave' each irrigation cycle moving from head- to tail enders. The respawn function and the irrigation parameters (which are part of the function) describe the irrigation system.

Respawn function: The respawn function prescribes the amount of water that respawns each irrigation cycle based on the total tax paid by the farmers. This function is based on Janssen et al. (2011). It is a logistic growth function (see equation 1). This function is modified to allow for a flexible number of farmers, which would impact the K, k and r (see appendix 8.1 for the exact equation).

$$R = \frac{K}{1 + e^{-k(\sum tax - r)}}$$

Equation 1: *Where R is the respawn value of the water, K is the carrying capacity, k the logistic growth rate (steepness of the function), and r is the function's mid point. The summation of tax is the total tax by the farmers.*

Irrigation parameters: The resource respawn function is characterized by irrigation parameters. These parameters are fixed for each model run, but vary between model runs. The effect of the parameters on the respawn function, and thus on the system, are explained below (and graphed in figure 2).

- The carrying capacity (K)[3]: the maximum amount of water produced by the irrigation system each cycle and the starting value of each model's run. It is a measure for the abundance of resources in the system. A higher K scales linearly with the abundance of resources in the system.
- The function's midpoint (r)[3]: at what tax value half the value of K is reached. This represents the difficulty of the collective effort to transform the tax in water; the higher r, the less resources is respawned for a given tax.

The logistic growth rate (k) informs about the steepness of the function around point r. This represents how gradual the function transitions from 0 to the carrying capacity. In this model, the overall form of the curve is kept consistent to resemble as close as possible the logistic growth function used in Janssen et al. (2011). It only varies based on the number of farmers (See appendix 8.1), and is therefore not an additional independent variables in the model.

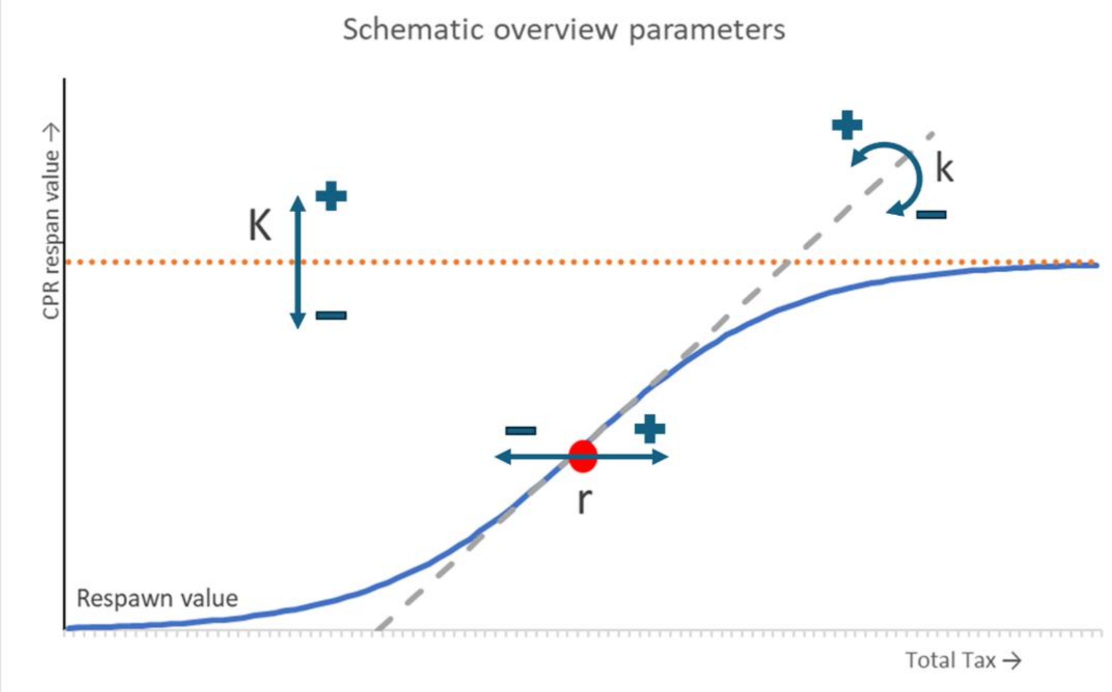

Fig. 2. *Irrigation parameters and their effect on the respawn value*

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[3] Taken strictly, both K and r should be named the carrying capacity *factor* and function's midpoint *factor* respectively, since it is the weight given to the standard K and r (see appendix 8.1 for the complete equation). The standard K is 20 units of water times the number of farmers, and the standard r is 5 units of energy times the number of farmers. This allows for a flexible number of farmers. However, in the interest of simplicity, this distinction is not made further since it does not impact the logic of the use of K and r. For example, a higher carrying capacity factor still results in a higher K.

3.2.3 Institutions

The operational institution dictates, whenever active, how much the farmers extract and invest. The collective-choice rules prescribe how the operational institution is formed. Both are described by their function, form, and institutional parameters.

Function: Periodically, the farmers have the opportunity to agree to an operational institution. They agree to this when a certain share of farmers do not have enough water. When they agree to install an operational institution, each farmer votes again to decide the height of the mandatory extraction (X), the condition they have to consider (y), and taxation height (Z). Each farmer votes for their own tactic, and the most common X, Y, and Z is selected as the new operational rule. From this point, the agents must comply with this shared rule rather than performing their own individual strategies. After the same period, there is a new chance for the farmers to change/install an new operational institution.

Form: The operational institutions is designed based on the ADICO-grammar by Crawford and Ostrom (1995). The use of this shared language makes it easier to discuss different institutional arrangements among the scientific community, and is based on the ABM in Ghorbani et al. (2017). ADICO structures institutions into five parts:

1. **A**ttribute: which attributes describe the subjects of the institution?
   This paper: **The farmers in the model**
2. **D**eontic: do the actors have the permission, obligation, or prohibition to perform the action.
   This paper: The farmers in the model are **obliged**
3. A**i**m: the action that is or is not allowed.
   This paper: The farmers in the model are obliged **to extract X or invest Z units**
4. **C**ondition: under which conditions do the institution apply
   This paper: The farmers in the model are obliged to extract X or invest Z units **when Y/ if they have sufficient energy**
5. **O**r else: what is the sanction the actor faces if it defies the institution?
   This paper does currently not incorporated punishment with the goal to cleanly separate the effects of the 'base' institution from a complicated punishment system. In the discussion, more attention is paid to this subject. It would look like this:
   The farmers in the model are obliged to extract X or invest Z units vest in the summer, or **they have to pay a fine.**

Institutional parameters: The farmers can only vote on the operational rules, and the collective-choice rules dictate how the operational institution is constructed in the model. The collective-choice rules are exogenous (decided on by me, the designer of the model), and are characterised by the institutional parameters.

- *Institution time:* the time between voting rounds
- *Minimal energy level*: The minimum energy level required for a farmer's well-being. Falling below this threshold causes the farmer to vote for a (change of) operational institution. This is the same variable as the minimal energy level in the farmer parameters.
- *Voting threshold:* the share of farmers needed to vote for a (change of) operational institution before it is installed.
- *Institution opportunity*: how often a voting round is held in a single model run. The institution opportunity times the institutional time results in the duration of a single model's run.

3.3 Model outcome

This model intents to study the conditions that promote the emergence and success of stable operational institutions. These conditions, which are the previously described farmer parameters, irrigation system parameters, and institutional parameters, act as the independent variables. The stability of the resulting operational institution is the dependent variable, and is based on Ghorbani et al. (2017). The success of the resulting institution is hereafter evaluated.

3.3.1 Institutional stability

There are three possible states for the stability of the operational institution:

1) **No operational institution:** during the model's run, no operational institution is ever established. This happens when a sufficient number of farmers are able to secure enough energy without ever needing to establish an operational institution.
2) **An unstable operational institution**: If farmers vote to change an operational institution after its initial implementation, it is considered unstable. However, it has the capacity to turn in a stable institution if it can remain over time.
3) **A stable operational institution**: after the instalment of an operational institution, farmers experience sufficient energy levels and do not vote for changes in the subsequent round. The institution is required to "survive" two consecutive voting rounds before it is classified as stable.

3.3.2 Institutional success

This paper operationalizes the success of operational institutions based on Agrawal's (2001) definition of sustainable CPR use: sufficient and fair extraction for users, and protection from depletion for the CPR. This entails three key elements: the state of the CPR system, sufficient extraction by the farmers, and fairness in extraction. These are evaluated in the following way:

- *CPR state:* this paper judges the state of depletion of the CPR directly based on the respawn value of the CPR. Higher respawn values indicate that the resource is not depleted, and is therefore deemed more successful.
- *Sufficient extraction:* this paper judges this based on the energy level of the farmers: if the farmers have high energy, they could apparently extract enough resources from the system.
- *Fairness between farmers:* to see if the farmers come to some form of fairness, a simple definition of wealth equality is used. This is calculated by the Gini-coefficient of the energy levels between the farmers (Hasell & Roser, 2023).

3.4 Model calibration

The model is coded in Netlogo v5.3.1 (Wilensky, 1999). After the conceptual design of the model, an appropriate parameter space should be chosen. A parameter space is the range of possible parameter settings. The right calibration is crucial for two main reasons. First, it ensures the ABM functions correctly, preventing (too) unrealistic scenario's to be modelled. Second, it allows to focus on the most intriguing system behaviours. These often occur at tipping points (where the system abruptly transitions between states) or where the model exhibits non-linear dynamics (Broeke et al., 2016).

The appropriate parameter space is defined as parameter values that are both realistic (informed by existing literature) and lead to a balanced distribution of model outcomes. This is an iterative process of strategically adjusting the parameter space. The starting point of this process was the model of Ghorbani et al. (2017), Janssen et al. (2011) and sometimes educated guesses (see table 2, last column). This process resulted in a parameter space in Table 2 that generates a near-equal distribution of stable (31%), unstable (34%), and non-existent (35%) operational institutions. The equal distribution makes sure that the tipping points are included in the analysis.

Table 2. Independent variables as farmer, CPR, and institutional parameters.

Category	Parameter	Unit	Range tested	Source starting point iteration
Farmer parameters	Minimal energy	E	5-47	Ghorbani et al. (2017)
	Energy use	E	.75 – 5.25	Guess
	Neighbourhood range	farmers	1-4	Janssen et al. (2011)
	Innovation rate	-	0 – 0.3	Ghorbani et al. (2017)
	Number of farmers	farmers	7 - 13	Janssen et al. (2011)
CPR parameters	Carrying capacity (K)	E	0.42 – 1.92 (see footnote 3, p12 for more information)	Janssen et al. (2011)
	Respawn function's midpoint (r)	E	0.24 - 0.8 (see footnote 3, p12 for more information)	Janssen et al. (2011)
Institutional parameters	Institution time	ticks	250 - 650	Ghorbani et al. (2017)
	Voting threshold	% farmers	30 - 75	Ghorbani et al. (2017)
	Installation opportunity		15 - 24	Ghorbani et al. (2017)

3.5 Model analysis

A global sensitivity analysis (Broeke et al., 2016) is used to identify the conditions under which stable operational institutions emerges and how they perform. The model is run 10.000 times, each time with a random parameter set drawn from the defined parameter space. By analysing the model's outputs in relation to these varying parameter settings in R-studio (2023), the influence of individual parameters can be estimated using standard regression models. While statistics could offer valuable insights, it also necessitates cautious interpretation of the outcomes. Running the model thousands of times generates a vast amount of data points, which can increase the risk of p-hacking in the subsequent regression analysis. P-hacking refers to the misleading identification of statistically significant patterns simply due to the abundance of data (Wasserstein & Lazar, 2016). It is important to be aware of this potential pitfall, and draw no conclusions that might not be there. Furthermore, due to the abstract nature of the ABM, the exact parameter values hold less significance as they do not have direct real-world meaning. Therefore, focusing on trends and relationships is more informative. For this reason, figures of the results are provided in the result section. This makes it easier to see the positive/negative correlations and the relative size of the effect, without focusing on specific values.

The exact regression outcomes are given in Appendix 8.2. First, the conditions under which any operational institutions (stable or unstable) is more likely to emerge is assessed with a logit regression. Subsequently, another logit regression is used to identify the factors influencing an institution's stability (stable vs unstable). Finally, I quantify the performance of the three institution types (no institution, stable institution, and unstable institution) using Ordinary Least Squares (OLS) regressions. These regressions consider the respawn value of the irrigation system, the average energy level of the farmers, and the Gini-coefficient of farmer energy levels as outcome variables.

4 Results

This chapter gives a description of the obtained the results of the ABM. First, under which conditions do (stable) operational institutions emerge. Secondly, the success of the different types of stability of the operational institution is given.

4.1 Emergence of stable operational institutions

4.1.1 CPR parameters

The CPR parameters, K (carrying capacity) and r (respawn function's midpoint), were the most influential factors for (stable) institutional emergence. Both K and r serve as measures of resource abundance within the model. The model demonstrates a seemingly straightforward relationship between resource abundance and the likelihood of (stable) operational institutions emerging: a greater CPR availability (a higher carrying capacity (K) and a lower function's midpoint (r)) corresponds with a decreased chance of any institutions forming. However, if institutions do emerge in a resource abundant scenario, they are more likely to be stable. Conversely, a lower CPR availability (lower K and higher r) is correlated to a lower probability of operational institutions arising, and any institutions formed tend to be unstable. In essence, with greater CPR availability (higher K or lower r), the model favours either stable institutions or no institutions at all.

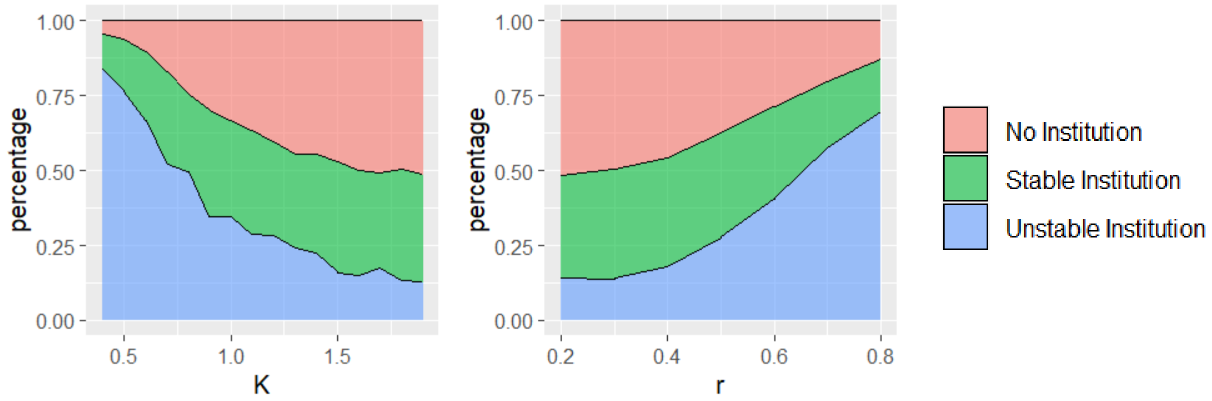

Fig. 3. *Probability of institutional state varied over K and r (red: no institution, green: stable institution, and blue: unstable institutions). These plots should be interpreted as follows: if for a parameter we see that the probability of state from 0-0.5 is blue, the space from 0.5-0.8 is green and the space from 0.8-1 is red, then for that parameter there is a 50% probability of ending up with an unstable institution, 30% chance of a stable institution, and 20% chance of no institutions at all.*

However, figure 4 reveals a specific interaction between K and r for fostering stable operational institutions (green). As described, when CPR is scares (K is low and r is high) depicted in the top left corner of the figure, the model observes just unstable institutions (blue). Conversely, the bottom right corner represents abundant CPR availability (high K and low r values), where fewer operational institutions are established overall (shown in red). Stable institutions (shown in green) can be seen between these regions, roughly from bottom left to top right. This signifies the balanced influence of K and r.

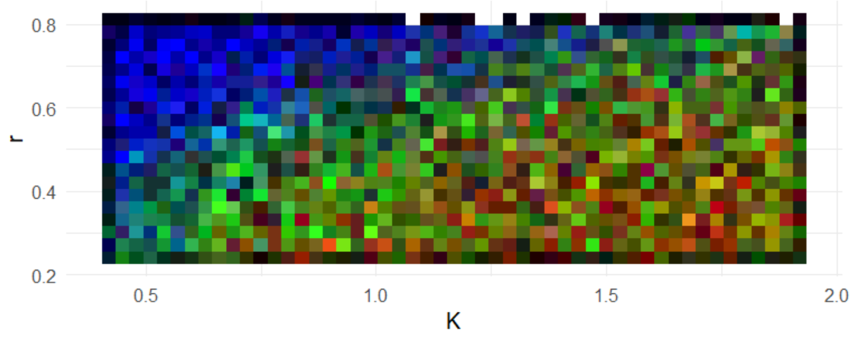

Fig. 4. *Frequency of institutional state (red: no institution, green: stable institution, and blue: unstable institutions) by K and r.*

4.1.2 Farmer parameters

For the farmer parameters, energy use (the passive decline of energy between irrigation cycles) had the strongest influence on the emergence of operational institutions. Higher energy use is positively correlated with overall institutional formation, but these institutions were increasingly more likely to be unstable. There is a negative correlation between innovation rate (the tendency of farmers to choose a random new tactic) and the emergence of institutions. The other parameters have seemingly little impact on the emergence and stability of the institution.

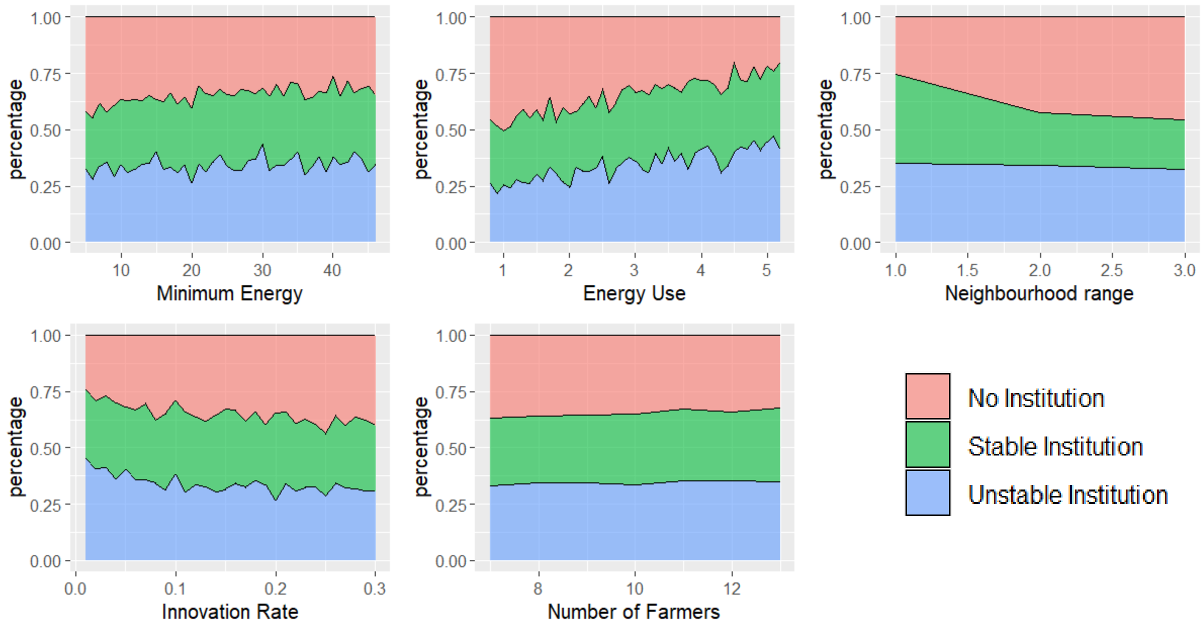

Fig. 5. *Probability of institutional state (red: no institution, green: stable institution, and blue: unstable institutions) varied over farmer parameters (minimum energy, energy use, neighbourhood range, innovation rate, and number of farmers). See figure 3 for the interpretation.*

4.1.3 Institutional parameters

For the institutional parameters, the institutional threshold (the majority share of farmers needed for forming or changing an institution) has the strongest impact on the emergence of any operational institution. The institution duration (time between voting rounds) and institution opportunity (how often voting round occurred in a single model run) showed negligible correlations with the formation of (stable) institutions. Finally, the minimum energy level (triggering a farmer's vote for institutional change, and triggering a tactic shift of the farmer) positively correlated with overall institutional emergence but did not significantly affect its stability.

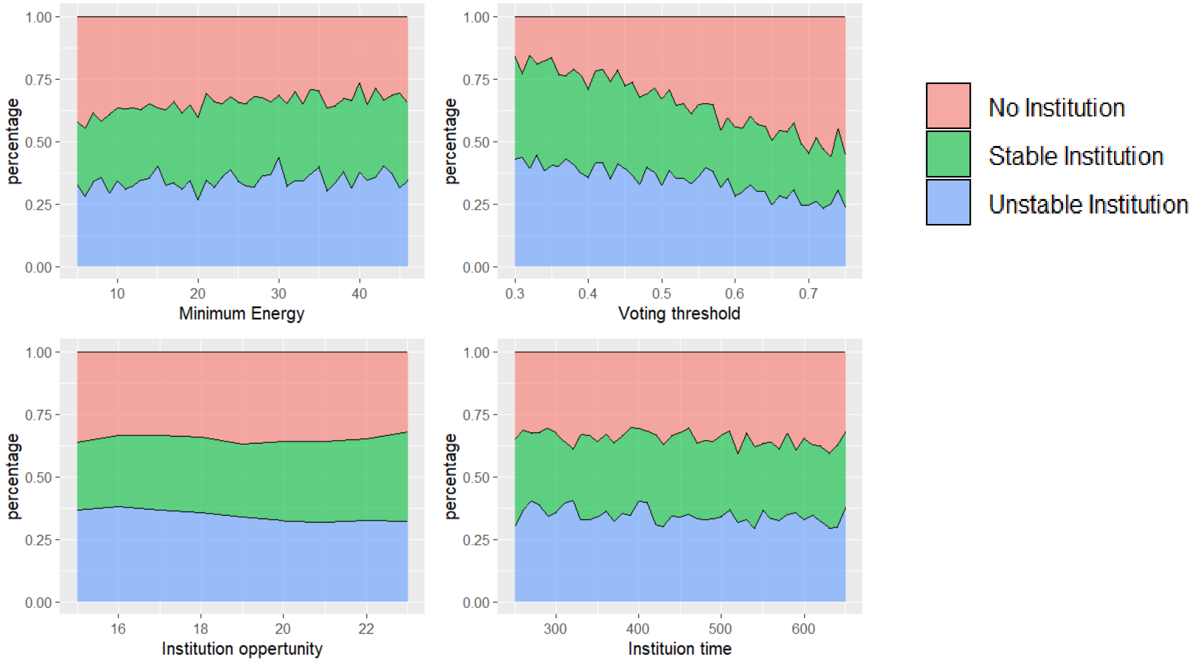

Fig. 6. *Probability of institutional state (red: no institution, green: stable institution, and blue: unstable institutions) varied over institutional parameters (minimum energy, voting threshold, institution opportunity, and institutional time. See figure 3 for the interpretation.*

For more detail, see Appendix 8.2 for the logit regressions on the conditions of operational institutional stability.

4.2 Institutional success

Having identified the parameters influencing the emergence of stable operational institutions emergence, the success of these institutions is judged. Figure 7 shows that the CPR respawn value is higher in scenarios with stable or no operational institutions, indicating a more sustainable resource state. Conversely, unstable institutions are associated with resource depletion. The average farmer's energy remains high (near the maximum of 200) in both no-institution and stable-institution settings. However, unstable institutions lead to very low energy levels for farmers. Wealth distribution is also more equal in the no-institution and stable-institution states, as depicted by a lower Gini-coefficient. But in cases where there was an unstable operational institution, the farmers at the head-end of the irrigation system monopolizes the CPR, leaving almost nothing for others and creating a very unequal wealth distribution. Overall, these findings suggest that both stable and no institutions are correlated with more successful outcomes compared to unstable institutions.

For more detail, see the OLS regressions in appendix 8.3.

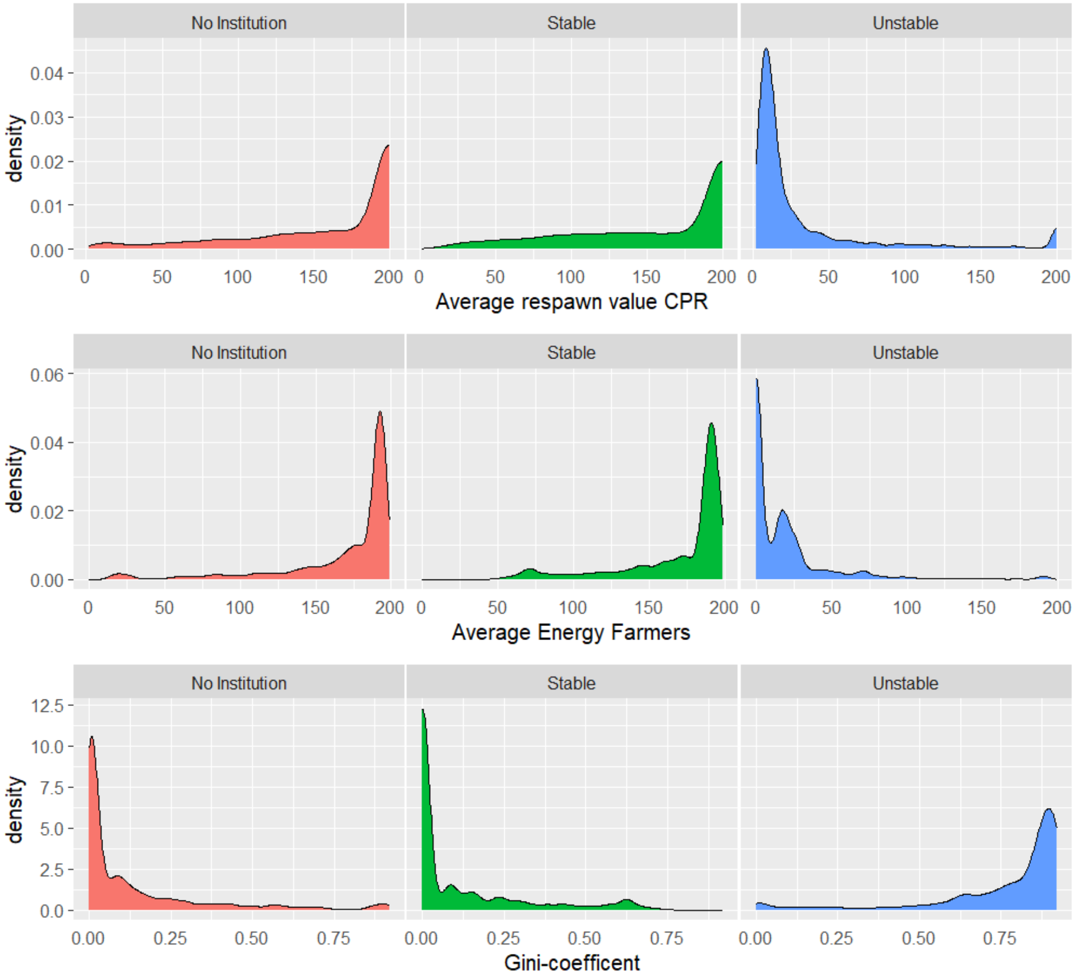

Fig. 7. *The performances of each type of institution. From top to bottom: CPR respawn value, average energy of farmer, and the Gini-coefficient of farmer's energy. Left to right: Red: no institutions, green: stable institutions, and blue: unstable institutions.*

5 Discussion

5.1 Interpretation and contextualisation of results

This ABM explore the conditions for the emergence and success of stable operational institutions for mobile CPR units. Overall, this study finds that stable operational institutions are related to success of the system. This is in agreement with the results of the ABM with immobile CPR units by Ghorbani et al. (2017). Retrospectively, this should not be a surprise based on the definitions of stability and how this modelled: only if the farmers have enough energy, they allow the institution to be stable. In a sense stable institutions are always successful. However, the ABM in this paper shows that the success of stable institutions is greater than what can be expected from the definition of stability, and from the comparison with Ghorbani et al. (2017). Ghorbani et al. (2017) found that stable institutions produced an energy level just above the minimal threshold for farmers to vote for change. When this would be translated to the current ABM, it is expected that just enough farmers (to stay above the voting threshold) can extract just enough resources (to stay above the minimal energy value). However, stable institutions are not found to be just successful enough to prevent a voting threshold, they produce such a optimal result that the farmers are at (nearly) the maximal energy levels. The added value of stable institution of mobile CPR units could be explained by Schlager et al. (1994). They concluded that the heightened uncertainty about the location and quantity of CPR would result in an optimal institution that improved certainty about other aspects of the system. The stability of the operational institution is such certainty, which could explain the above expected results from stable operational institutions.

Certain farmer, CPR, and institutional parameters are found to be more correlated with stable operational institutions, and through stable institutions, success. The effects of the institutional parameters can be seen as the most notable findings of this paper, since it differs significantly from the finding from Ghorbani et al. (2017). These differences suggest that fundamental differences between the formation and success of operational institutional of mobile and immobile CPR units exists. Most notably, the voting threshold was found to be significant and impactful in this ABM but not in Ghorbani et al. (2017). Lower voting thresholds in this study are correlated with more operational institutions and more successful outcomes. The lower voting threshold means that a smaller fraction of the farmer population could call for a change of operational institutions. The significance of this parameter potentially reflects the significance of the power asymmetry inherent in the irrigation dilemma (Janssen & Rollins, 2012). To overcome this power asymmetry, and prevent head-enders from exploiting the system, collective-choice rules that empower the 'repressed' minority could counteract this effect. Therefore, this study suggests that listening to minority groups in mobile CPR management becomes even more crucial for the success of operational institutions.

Interestingly, other institutional parameters, such as institution emergence time and institution opportunity, did not show significant impacts. This is unexpected, as too brief emergence times should lead to the removal of successful institutions before their benefits are ‘felt’ by the farmers. Potentially, the calibration of these parameters may not have fully captured the relevant range the model.

The best predictor of stable institutions are the CPR parameters: the combination of K (carrying capacity) and r (respawn function’s midpoint). Similar to Ghorbani et al. (2017), this study finds an optimal range between the both where stable institutions frequently arise. Ostrom (2005) also described this optimal zone for resource availability for the emergence of practical institutions. When the CPR is too abundant, the need for an institution diminishes, as most users can freely access what they need without significantly impacting others. On the other hand, if the CPR is too scarce, no matter what rules the users institute, success becomes almost impossible. Only within a specific range of resource availability do the bandwidths of necessity and feasibility of stable institutions overlap.

The farmer’s characteristics are found to be less impactful on the formation of stable operational institutions, although two still had effect. The energy use, which is the ‘cost of living’ for the farmer, was found to be correlated with the emergence of institutions. This can be explained similarly as the resource characteristics, as the energy use is (one of) the factors that decide what the value of a water/energy/tax unit is. When the cost of living is higher, a greater amount of resources is required to maintain the same level of well-being for the farmers. The innovation rate, determining how fast farmers would change to a random tactic vs copy a successful neighbour, was negatively correlated with the formation of stable operational institutions. This means that farmers were better of when they copied successful neighbours instead of inventing a complete new strategy. This is in contrast to Ghorbani et al. (2017). However, they included the possibility of cheating in their latest ABM. An agent cheats when his own tactic differs dramatically from the installed operational institution, and this chance is higher when the farmers are inclined to choose a random new tactic. The significance of this parameter should be further investigated when cheating is allowed in this model too. The other farmer parameters were not significant

Consistent with the empirical results of Janssen et al. (2011), the ABM demonstrates that without a stable operational institution, the order of resource extraction leads to inequality among farmers, with head-enders exploiting the situation. However, this behaviour is ultimately devastating for both the head- as well as the tail-enders. When institutions promote equality among farmers, they all benefit. This suggests a correlation between institutional effectiveness and equality. Ostrom and Gardner (1993) further emphasizes this point. She highlights how self-organizing institutions can overcome these asymmetries in CPR management by fostering awareness of mutual dependence. After all, head-enders may rely on tail-enders for long-term system maintenance. However, this ABM does not explicitly address this awareness of interdependence, which could be a valuable future exploration

5.2 Limitations and ways forward

This ABM highlights the importance of stable operational institutions for promoting sustainability for mobile CPR units. The validation of the model is partially assumed through the similarity with Ghorbani et al. (2017). It can prove insightful to do a validation, based on case studies that involve mobile resources.

Looking critically to the assumptions of this ABM, the stability itself is a topic of discussion. In recent year, a growing emphasis on resilient governance has been seen, advocating for adaptive institutions that can adjust to rapid changes (Folke et al., 2005). Given the increased natural disasters (Van Aalst, 2006), a valuable future expansion of this ABM could be the inclusion of system shocks. For example, an one-time event halving the system's carrying capacity (representing, for example, a sudden drought impacting the irrigation system). This addition would allow for a comparative analysis of how stable versus adaptive operational institutions respond to such challenges.

A further interesting research direction involves investigating different levels of self-emerging institutions. For example, the impact of self-emerging collective-choice rules, and how the stability on this level impacts the sustainability of the system. However, coding such a scenario in the current ABM framework would likely be very complex and potentially requires a different ABM design. A more readily achievable extension of this ABM is to complete the ADICO framework; without the possibility to cheat the institution and a sanctioning system for the cheaters (the ‘Or else’ element), the institutions in this ABM should formally be called ‘norms’. Ghorbani et al. (2017) observed a higher prevalence of cheating within stable operational institutions, ultimately undermining their overall effectiveness, and it would be interesting to study if the same effect applies to mobile CPR units.

5.3 Scientific and social relevance

This research presents a novel contribution to the field by merging the irrigation dilemma with an agent-based model (ABM) for studying institutional formation. This model opens avenues for broader application beyond the specific research question addressed in this paper. Firstly, the allows for the simulation of specific irrigation systems by incorporating real-world parameter values. This enables the exploration of diverse irrigation scenarios and the specific conditions needed to promote the emergence of stable institutions. Secondly, the model could reach beyond irrigation systems. Systems exhibiting characteristics similar to the irrigation dilemma can also be investigated. As an illustration, Janssen and Rollins (2012) demonstrated the a shared Wi-Fi network with limited bandwidth share similarities to the irrigation dilemma, highlighting its potential for diverse contexts. Finally, the findings generated by the ABM provide a fresh perspective on the extensive body of literature on institutions. This contribution adds to the existing knowledge base on this complex topic.

Despite these intriguing avenues for future research, the ABM's conclusions already offer practical societal insights. Irrigation systems, or other mobile CPR unit systems, are suggested to significantly benefit from the implementation of stable institutions. To enhance the likelihood of establishing successful and stable operational institutions, we can directly target the conditions fostering such stability. The study identified resource abundance as the most impactful factor. However, the abundance of a CPR can often not directly be impacted. However, collective-choice rules also play a significant role in the success of operational institutions. This is particularly noteworthy because, unlike resource availability and farmer characteristics, collective-choice rules offer greater potential for direct modification (although still subject to constitutional institutions). The research suggests that SES with mobile CPR units could achieve more sustainable and profitable institutions by lowering the institutional threshold. In simpler terms, allowing smaller coalitions of dissatisfied participants to trigger institutional reform or creation could be beneficial.

6 Conclusion

In sum, the success of common-pool resource problems is determined by the institutions the users can agree to. Each situation requires a different set of institutions, and the conditions of the system can indicate which institution is needed. This thesis set out to answer the research question: *how does the mobility of the common-pool resource units affect the formation and success of stable institutions in an agent-based model?* The designed agent-based model illustrates that the mobility of the resource unit makes a crucial difference in formation of the institutions. It showed that different user-, environmental-, and institutional conditions are required to form stable self-emerging institutions in comparison with non-mobile resource units. Most surprisingly, the results indicate a key role for certain collective-choice rules in the stability (and ultimately success) of operational institutions, such as the minimal voting threshold. This has direct policy implications, as the results suggests that an increase of potential influence of represent minorities is beneficial for the system as a whole.

The success of stable institutions is at a first glance not different from situations involving immobile resource units; both mobile and immobile resource units thrive under stable institutions. This could be the results of the design of the model, and how stability is defined. However, deeper inspection of this model finds that stable institutions perform better than what could be expected from a comparison with immobile resources. This is possibly explained by the increased need for certainty, since the mobility of the resource brings a factor of intrinsic uncertainty.

The model itself is also valuable scientific result of this thesis, as it novel in the combination of the irrigation dilemma and the emergence of operational institutions. This opens the possibility to more applied ABMs, or expansions such as the inclusion of cheating farmers.

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8 Appendix

8.1 Respawn equation

$$R = \frac{K \ * 20 \ * \ \#farmers}{1 \ + \ e^{\frac{-1}{1+ \#farmers} * (\sum tax \, -(r \, *5 * \#farmers))}}$$

This equation is based on table 2 given in Janssen et al. (2011, p. 1593). The adjustments to the equation were needed to contain the overall shape of the function, while at the same time allowing a flexible number of farmers.

8.2 Logit regressions

8.2.1 No institution vs any institution (reference)

Coefficient	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	-2.1890985	0.2910342	- 7.522	5.40e-14	***
Minimum-energy	-0.0137142	0.0020250	- 6.773	1.26e-11	***
Energy-use	-0.3276945	0.0192505	-17.023	< 2e-16	***
K	1.9065146	0.0605944	31.464	< 2e-16	***
r	-4.3023860	0.1592298	-27.020	< 2e-16	***
Innovation-rate	2.4111036	0.2832697	8.512	< 2e-16	***
Institution-time	0.0008593	0.0002101	4.090	4.32e-05	***
Voting-threshold	4.7623524	0.1959600	24.303	< 2e-16	***
Institution-opportunity	-0.0079873	0.0094306	- 0.847	0.397021	

```
---
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for binomial family taken to be 1)

 Null deviance: 12910 on 9999 degrees of freedom
Residual deviance: 10121 on 9990 degrees of freedom
AIC: 10141

Number of Fisher Scoring iterations: 4
```

8.2.2 Stable institutions vs unstable institutions (reference)

Coefficients	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	-0.9388940	0.3457971	- 2.715	0.00662	**
Minimum-energy	0.0036203	0.0024729	- 1.464	0.14320	
Energy-use	-0.2294328	0.0235575	- 9.739	< 2e-16	***
K	2.4752323	0.0794874	31.140	< 2e-16	***
r	-6.7667714	0.2131875	-31.741	< 2e-16	***
Innovation-rate	2.1571168	0.3435801	6.278	3.42e-10	***
Institution-time	0.0006883	0.0002574	2.674	0.00750	**
Voting-threshold	1.0593698	0.2335857	4.535	5.75e-06	***
Institution-opportunity	0.0811721	0.0114467	7.091	1.33e-12	***

```
---
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for binomial family taken to be 1)

 Null deviance: 9034.8 on 6530 degrees of freedom
```

```
Residual deviance: 6792.8 on 6521 degrees of freedom
AIC: 6812.8

Number of Fisher Scoring iterations: 4
```

8.3 OLS regressions

8.3.1 Farmer Energy

```
Residuals:
 Min 1Q Median 3Q Max
-160.040 -13.653 4.735 19.499 176.512
```

Coefficients	Estimate	Std. Error	t value	Pr(>|t|)	Significance
(Intercept)	1.708e+02	2.883e+00	59.247	< 2e-16	***
Carrying capacity	3.153e+01	8.800e-01	35.825	< 2e-16	***
r	-3.903e+01	2.342e+00	-16.666	< 2e-16	***
Innovation-rate	1.454e+01	3.924e+00	3.705	0.000212	***
Neighbourhood range	4.005e-01	3.119e-01	1.284	0.199041	
Institution-time	1.229e-02	2.918e-03	4.210	2.58e-05	***
Voting-threshold`	-4.756e+01	2.692e+00	-17.666	< 2e-16	***
Energy-use	-3.213e+00	2.655e-01	-12.103	< 2e-16	***
Minimum-energy	4.022e-03	2.809e-02	0.143	0.886175	
stability-stable	3.031e+00	8.996e-01	3.369	0.000758	***
stability-unstable	-1.309e+02	1.041e+00	-125.773	< 2e-16	***

```
---
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 33.86 on 9989 degrees of freedom
Multiple R-squared: 0.8205,    Adjusted R-squared: 0.8203
F-statistic: 4567 on 10 and 9989 DF, p-value: < 2.2e-16
```

8.3.2 CPR respawn value

```
Residuals:
 Min 1Q Median 3Q Max
-168.994 -22.469 2.888 28.034 178.279
```

Coefficients	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	129.394515	3.923206	32.982	< 2e-16	***
Carrying capacity	60.110101	1.197446	50.199	< 2e-16	***
r	- 55.976636	3.186609	-17.566	< 2e-16	***
Innovation-rate	11.978751	5.338864	2.244	0.024874	*
Neighbourhood range	- 1.475923	0.424337	- 3.478	0.000507	***
Institution-time	- 0.003679	0.003971	- 0.927	0.354129	
Voting-threshold	- 45.240791	3.663515	-12.349	< 2e-16	***
Energy-use	0.814327	0.361222	2.254	0.024194	*
Minimum-energy	0.064734	0.038229	1.693	0.090426	.
stability-stable	- 0.917309	1.224022	- 0.749	0.453620	
stability-unstable	- 96.404681	1.416531	-68.057	< 2e-16	***

```
---
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
Residual standard error: 46.07 on 9989 degrees of freedom
Multiple R-squared: 0.6591,    Adjusted R-squared: 0.6587
F-statistic: 1931 on 10 and 9989 DF, p-value: < 2.2e-16
```

8.3.3 Gini-coefficient

```
Residuals:
 Min 1Q Median 3Q Max
-168.994 -22.469 2.888 28.034 178.279
```

Coefficients	Estimate	Std.Error	t value	Pr(>|t|)	
(Intercept)	129.394515	3.923206	32.982	< 2e-16	***
Carrying capacity	60.110101	1.197446	50.199	< 2e-16	***
r	- 55.976636	3.186609	-17.566	< 2e-16	***
Innovation-rate	11.978751	5.338864	2.244	0.024874	*
Neighbourhood range	- 1.475923	0.424337	- 3.478	0.000507	***
Institution-time	- 0.003679	0.003971	- 0.927	0.354129	
Voting-threshold	- 45.240791	3.663515	-12.349	< 2e-16	***
Energy-use	0.814327	0.361222	2.254	0.024194	*
Minimum-energy	0.064734	0.038229	1.693	0.090426	.
stability-stable	- 0.917309	1.224022	- 0.749	0.453620	
stability-unstable	- 96.404681	1.416531	-68.057	< 2e-16	***

```
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 46.07 on 9989 degrees of freedom
Multiple R-squared: 0.6591,    Adjusted R-squared: 0.6587
F-statistic: 1931 on 10 and 9989 DF, p-value: < 2.2e-16
```