Agent-Based Model Application for Resource Management Analysis

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Abstract: Due to climate change and population growth, the agriculture sector has been faced with two challenges; securing water and food and transferring into sustainable resource management. To systematize resource management which currently mainly relies on farmers' experience, digital technologies have been developed. Considering current tighter resource availability, it is desirable to examine resource management behavior of beneficiaries using scarce resources to analyze resilience and adaptability of institutions. In this study, we analyzed factors of water use behavior of Water Users Associations (WUAs) to solve water allocation problem with Agent-Based Model (ABM). The simulation results show that factors of water use behavior were water resources and the existence of different water use laws, and downstream WUAs developed adaptation methods. To enhance sustainable resource management, ABM can be applied to analyze factors and their rules and/or laws to understand what enhances resilience and adaptability of institutions.

1 INTRODUCTION

The agriculture sector has been faced with challenges to secure water and food. To solve these challenges, digital technologies such as Artificial Intelligence (AI) and Internet of Things have the potential to create new systems to improve productivity (Trendov *et al.*, 2019). AI can systematize agricultural management which mainly relies on farmers' experience. It will also help pass accumulated valuable agricultural knowledge to the next generation (Ministry of Agriculture, Forestry and Fisheries in Japan).

To understand conventional water use rules of farmers, Lansing and Kremer (1993) analyzed farmers' decision-making about cropping patterns in irrigated rice farming area. They investigated 172 water users' associations (WUAs) located in two rivers' basins in south-central Bali and found that the WUAs had two constraints; water sharing and pest control. If WUAs cooperatively fallowed large paddy fields during a certain period, pests could be killed. However, after the fallowing period, large paddy fields needed irrigation water at the same time, and it could pose water stress. In the basins, the WUAs were grouped, and all WUAs in a group had the same cropping pattern. With Agent-Based Modeling (ABM) and simulation, the study finds that water management of the WUAs decreases water stress and pest damage and optimizes rice yields. This result shows that, first, even with limited resources, beneficiaries can coordinate their behavior for sustainable and equal resource use. Second, it exemplifies that ABM is instrumental in analyzing resource use behavior.

Due to climate change and population growth, resource management has become more severe so that sustainability of current resource use by beneficiaries is in question. Therefore, it is desirable to examine the behavior of beneficiaries using scarce resources to analyze resilience and adaptability of institutions such as WUAs. In this study, we targeted irrigated rice farmers and analyzed factors of water use behavior of WUAs to solve the water allocation problem. For the analysis, we built an ABM by modifying Lansing and Kremer model. This study presents how digital technologies can help us analyze resource management, and suggests the potential of technologies such as ABM to improve resource management based on the analysis.

This paper is organized as follows: Section 2 describes water management in irrigated paddy fields

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of the target area in Bali, Indonesia. Section 3 presents how we replicated water use behavior of the target area with ABM. In Section 4, from simulation results, we show factors of water use behavior and, discuss the results in Section 5.

2 WATER MANAGEMENT IN IRRIGATED PADDY FIELDS

In this section, we take an example of WUGs in Bali and explain how farmers decide water management in irrigated paddy fields.

2.1 Subak System

Over the centuries, Balinese paddy terrace fields have been managed by traditional water users' association, Subak. A Subak is composed of all the paddy fields irrigated from a single water source such as a dam or a sluice, and its members are all landowners of the paddy fields (Geertz, 1980). The structure of a Subak is hierarchical and consists of Subak board members and members. The smallest groups in a Subak are sub-Subaks which are bounded by artificial or natural obstacles such as road and creek. A sub-Subak is the smallest unit of the decision making process in Subak system and should have the same cropping calendar. (Suradisastra et al., 2002). The uniqueness of Subak system is having a democratic organization whose rice cultivation roots in Balinese Hinduism, owning rules called Awig-awig, and performing rituals along with the stages of paddy growth (Suradisastra *et al.*, 2002).

Awig-awig has rules necessary for democratic management. It contains, for example, organization structure, term of Subak board members, frequency of Subak meeting, water allocation rules among Subak members, cropping pattern(s), communal works, and penalties (Nagano, 2011). One of the tasks of Subak board members, especially the head of Subak, is the creation of a seasonal water management plan. Although awig-awig defines water allocation rules and cropping pattern(s), depending on climate conditions and water use of other Subaks, in every cropping season water use adjustment is needed. For that reason, as Figure 1 shows, in the Subak meeting, all Subak members discuss a water management plan proposed by Subak board. Once a water management plan is endorsed by the majority of the Subak members, every Subak members are obligated to follow it. Hence, one Subak has one water management plan in a cropping season.

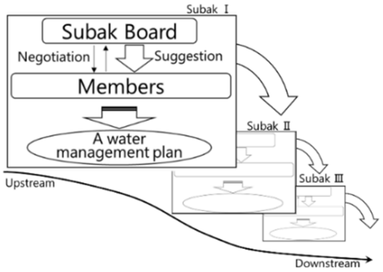

Figure 1: Decision flow of a water management plan.

2.2 Study Area

To understand the Subak system, we investigated five Subaks; Subak A, Subak B, Subak C, Subak D and Subak E located in downstream of Saba watershed in Buleleng regency, Province of Bali Island, Indonesia. Figure 2 shows the research location. While Subak A tended to have stable cropping calendars, Subak B through E changed cropping calendars every year. The five Subaks had shared a water resource taken from Saba intake weir for more than 50 years. Saba intake weir was located in Subak A so that Subak A had the power to manage the weir over other Subaks. Among sub-Subaks of Subak A spreading along the primary irrigation canal, two of them were the closest to Saba intake weir. After the two sub-Subaks (hereinafter called group A1), the primary irrigation canal was diverted into two irrigation canals. One of two irrigation canals irrigated the rest of sub-Subaks of Subak A (hereinafter called group A2), and then Subak B. The other canal irrigated in order of Subak C, Subak D, and Subak E. As Table 1 shows, among five Subaks, Subak A had widest paddy fields and most Subak numbers. The tail users, Subak D and Subak E, had the second widest paddy fields.

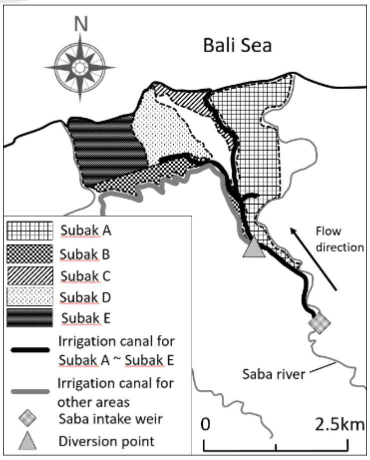

Figure 2: Location of the study area.

Rice cropping consisted of paddling and leveling (hereinafter called paddling), rice growth and harvesting. Paddling needed a substantial amount of irrigation water continuously. In fact, from 20% to 30% of the total water requirement of single rice cultivation is used during paddling (Sembiring *et al.*, 2011). After rice transplantation, the rice growth period continued around 90 days. In this period, paddy fields kept 10 to 15 cm of water depth until around 10 days before harvesting.

To maximize rice production, Subaks needed to fit their water use into a rainfall pattern. Figure 3 shows a normal rainfall pattern from October 2004 to September 2005 observed by Agency of Meteorology, Climatology and Geophysics. The rainy season started in October, and after the peak of rainfall reached in February, rainfall decreased to shift to the dry season starting from April. From July to September, it rarely rained. To grow paddy as many as possible in a year, Subaks generally started paddling of the first rice cropping season when the rainy season started, finished one rice cultivation within four months, and continuously grew paddy three times a year. However, in the dry season, if Subak members predicted water sacristy would occur, they grew non-paddy crop(s) without using irrigation water. Practically, internal and external conditions irregularly changed so that Subaks decided their water use seasonally. To replicate their decision-making process of water use with ABM, we interviewed five heads of Subak from 2014 to 2016.

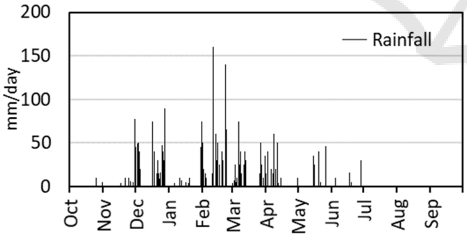

Figure 3: Daily rainfall amount in Subak A area from Oct. 2004 to Sep. 2005.

3 MODEL DEVELOPMENT

In this section, we explain our ABM. The model was developed to simulate the water allocation system of the study area. The model components and agent behavior were decided based on interview results.

3.1 Model Components

The water allocation phenomenon created by water use of each five Subak has been replicated in our ABM. The model components are an irrigation canal network consisting of Intake Weir and Irrigation Canals, Intake Points of agents, and agents which represent Subaks. Because Subak A worked as two groups, group 1 and group 2, we created two agents for Subak A. Consequently, our ABM has six agents, Agent A1, Agent A2, Agent B, Agent C, Agent D and Agent E. The six agents are aligned along Irrigation Canals as they were observed and take water from Intake Points which were given one for each agent. The agents in this model know irrigation water flow from Intake Points, and Intake Weir inflow is ultimately shared among the agents. This information conveyance brings about adjustment of agents' water use to maximize rice yield. The paddy field sizes of agents are the same as the real sizes as Table 1 shows. The water use behavior of agents was defined based on interview results.

Table 1: Attributes of Subaks.

Subak		Rice field (ha)	Members (person)
A	Group A1	19	264
	Group A2	103	
B		21	44
C		17	34
D		71	156
E		71	132

3.2 Cropping Patterns

Subak A and the other Subaks had different cropping patterns. Subak A grew paddy four times and non-paddy crops once in two years thanks to abundant irrigation water. For Subak A, growing non-paddy crops was a purpose of pest control and soil restoration. The rice farmers in the study area experimentally knew that the rice yield was higher when the harvest season was from September to October. It was the reason why Subak A preferred to grow non-paddy crops from April to May to secure the rice yield of the next cropping season. On the contrary, Subak B, Subak C, Subak D, and Subak E changed cropping calendars and had double or triple rice cropping per year depending on seasonal water availability. If irrigation water seemed scarce to grow paddy in the third cropping season which was the later part of the dry season, they grew non-paddy crops requiring no irrigation water.

Therefore, our ABM had two sets of cropping patterns. Subak A had (paddy-paddy-paddy-paddy-nonpaddy) and (paddy-paddy-paddy-paddy-paddy), and Subak B, Subak C, Subak D and Subak E had (paddy-paddy-paddy) and (paddy-paddy-nonpaddy).

3.3 Customary Laws on Water Use

Owing to differences in water availability between Subak A and the other Subaks, customary laws describing their water use were different. In summary, customary laws of five Subaks defined four rice cropping phases; the beginning of the first rice cropping season, paddling, rice growing, and harvesting. Nonetheless, the general Subak system basically prescribes that all Subak members in a Subak have the same cropping pattern, exceptions were found in all five Subaks. Thus, here we focus on basic customary laws.

With abundant irrigation water, Subak A decided the beginning date of the first cropping season freely. It also usually didn't have to heed change of water availability to adjust the length of the paddling period. Consequently, the customary laws of Subak A tended to have fixed cropping calendars. Reflecting these features, we created three cropping calendars (Table 2).

On the contrary, due to lack of irrigation water, water use of the other Subaks, Subak B, Subak C, Subak D and Subak E changed cropping schedules depending on rainfall and availability of irrigation water. The other Subaks scheduled the beginning date of the first rice cropping season when the rainy season started, but in the event of low irrigation water supply, they staggered and scheduled the beginning date later than that of upstream Subaks. In addition to that, these Subaks seasonally adjusted length of the paddling periods depending especially on water availability. However, even with the adjustment if they estimated water scarcity would happen, non-paddy crops were chosen. The customary laws of the other Subaks illustrate that water use of other upstream Subak(s), especially Subak A is influential enough to change their water use because of lack of irrigation water. Following an annual change of rainfall patterns, Subak B through E change water use. This is the reason why their cropping calendars varied every year (Table 3).

Water use of Subak A influenced to the other Subaks, and the other Subaks adapted to changes of water flow caused by upstream Subaks, especially Subak A. Therefore, hereinafter, we refer to the set of customary laws of Subak A as "dominant laws", and the set of customary laws of Subak B through Subak E as "submissive laws". As Table 2 and Table 3 show, the main factor of both dominant laws and submissive laws was water resources. Therefore, from now, we will only consider water resources-related laws to simply replicate adjustment mechanisms of submissive laws.

Table 2: Customary laws of Subak A.

phase	Customary law	Factor
The beginning of the first rice cropping season	Freely decide the beginning date of the first rice cropping season	Water resources
Paddling	Adjust the paddling period depending on water availability and labor force	Water resources
		Labor force
Harvesting	Adjust the harvesting period depending on labor force	Labor force

Table 3: Customary laws of the others.

phase	Customary law	Factor
The beginning of the first rice cropping season	Set the beginning date of the first rice cropping season at the beginning of the rainy season	Water resources
	In the event of low water supply, stagger the beginning date of the first rice cropping season to set later than upstream Subaks.	Water resources
Paddling	Adjust the paddling period depending on water availability and labor force	Water resources
		Labor force
Rice growing	If estimated yield < 5 t/ha/season, plan non-paddy crops	Water resources
Harvesting	Adjust the harvesting period depending on labor force	Labor force

3.4 Adjustment of Cropping Calendars

Based on submissive laws, we set the model ran with ten-day time steps, and modeled the adjustment mechanism of two rice cropping phases; the beginning of the first rice cropping season and paddling. The two phases were governed by water resource-related laws so that the paddling period evaluation and yield were calculated on a demand-supply basis.

The paddling period evaluation is evaluated by:

$$R_{pad} = \frac{TS_{pad}}{TD_{pad} \times \mathrm{k}} \tag{1}$$

where, R_{pad} is the total water supply and demand ratio of the paddling period, TS_{pad} is total water supply of the paddling period(m^3), TD_{pad} is total water demand of the paddling period (m^3). k is a coefficient denoting the demand intensity of each agent. In our model, $TS_{pad} = TD_{pad}$ with (total rainfall amount of the paddling period + total irrigation water amount of the paddling period) $\geq TD_{pad}$, and TS_{pad} = (total rainfall amount of the paddling period + total irrigation water amount of the paddling period) with (total rainfall amount of the paddling period + total irrigation water amount of the paddling period) $< TD_{pad}$. As following research by Sembiring *et al.* (2011), we suppose that TD_{pad} is 200(mm/season). k is decided according to the results of water flow measurement; 3.5 is for Agent A1 and Agent A2, 2.5 is for Agent B, 1.5 is for Agent C and Agent D, and 1.0 is for Agent E.

Yield is calculated by:

$$\mathrm{y} = \frac{TS}{TD \times \mathrm{k}} \times y_{max} \tag{2}$$

where, y is yield (t/ha/season), TS is total water supply of the rice growth period (m^3); TD is the total water demand of the rice growth period (m^3). k is coefficient denoting demand intensity, and y_{max} is maximum yield (t/ha/season). In our model, TS is calculated as (1), TD is calculated on 20 (mm/day) basis referring to Japanese average, k is given as (1), and y_{max} is 9 (t/ha/season) according to our field research result. For the yield evaluation, the yield threshold for the first season and the second season is 7 (t/ha/season), and that for the third season is 5 (t/ha/season). We change the value of the yield threshold to replicate an actual decision.

With the formula (1) and (2), agents in our ABM optimize two phases of a given cropping pattern as Figure 4 shows. First of all, agents optimize their beginning date of the first rice cropping season. They adjust the paddling period of the first rice cropping season until R_{pad} becomes 1 and its length becomes the shortest among options. At the same time, if the evaluated first rice yield is below the yield threshold, agents stagger the beginning date until the first rice yield becomes equal to or above the yield threshold. Second, from the second cropping season, agents evaluate the adjustability of the paddling period, and if possible, optimize its length. Third, agents evaluate whether the second rice yield is equal to or above the yield threshold. If so, they start to adjust the third season. However, if the paddling period is not adjustable or rice yield is below the yield threshold, they grow non-paddy crops in the rest of the cropping year. When agents adjust the paddling period, they choose the shortest days from 20 days, 30days and 40 days. However, the rice growth period and the harvesting period are fixed, 90 days and 10 days respectively.

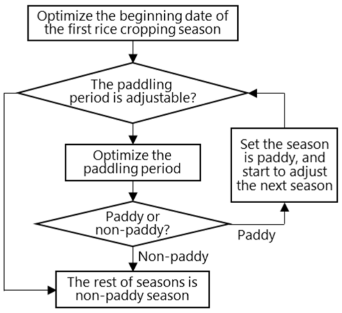

Figure 4: Adjustment process of cropping calendars.

3.5 External Conditions

As external conditions, we use two sets of secondary data of water resources; rainfall data observed in Subak A and Saba Intake weir inflow data observed by Bali River Basin Administration Office (Balai Wilayah Sungai Bali-Penida (BWS-BP). First, regarding rainfall data, to see water use behavior under normal rainfall patterns, we chose rainfall data from October 2000 to September 2002 and from October 2003 to September 2009. Second, as Intake Weir inflow in our ABM, we referred to Saba intake weir inflow data from January 2004 to March 2006. The data fluctuated by multiple reasons such as irrigation canal repair, unusual irrigation water request, and rainfall event so that, to simplify the seasonal fluctuation tendency, the initial Intake Weir inflow was set to 1750,000(m^3/day) in the rainy season and 122,500(m^3/day) in the dry season. In the simulation, we used 10-days data of both water resources.

4 SIMULATION RESULTS

In this section, we show simulation results that were conducted to examine the effects of dominant laws and submissive laws. First, we applied the same laws, submissive laws, to all six agents; Agent A1, Agent B, Agent A2, Agent C, Agent D, and Agent E. We simulated cropping calendars with seven different water volumes of Intake Weir flow and compared the number of cropping calendars among the six agents. Second, we applied the different laws; applied dominant laws to Agent A1 and Agent A2, and applied submissive laws to the others; Agent B, Agent C, Agent D, and Agent E. We simulated cropping calendars with the initial Intake Weir inflow and compared the number of cropping calendars with ones simulated when all agents had the same laws.

With submissive laws, our model creates cropping calendars randomly as the initial condition of agents. Specifically, before a simulation runs, agents have a cropping calendar coming from a cropping pattern with randomly selected paddling periods except for the beginning date of the first rice cropping. Following the interview results, all agents have October 1st as the initial beginning date. Once a simulation starts, the model continues running until cropping calendars of all agents converged. In every Intake Weir inflow, we got results of 100 simulations.

4.1 The Same Customary Laws

Table 4 shows the number of cropping calendars when all agents have the same laws; submissive laws. When Intake Weir inflow is the initial, the number of cropping calendars are one for Agent A1, Agent B, and Agent A2, two for Agent C and Agent D, and four for Agent E. When Intake Weir inflow increases more than the initial, in the end, all agents have the same cropping calendar. It shows that downstream agents produce a couple of cropping calendars to adapt to conditions of water scarcity, and when the irrigation water supply is enough, all agents yield one cropping calendar. Therefore, the selection of cropping calendars is affected by the amount of water resources.

Table 4: The number of cropping calendars with the same law.

The volume of Intake Weir inflow	Agent					
	A1	B	A2	C	D	E
The initial -10%	1	1	2	2	2	1
The initial	1	1	1	2	2	4
The initial +10%	1	1	1	2	2	1
The initial +20%	1	1	1	1	1	1
The initial +30%	1	1	1	1	1	1

4.2 The different Customary Laws

Here, the initial Intake Weir inflow was applied. We gave three fixed cropping calendars to Agent A1 and Agent A2 based on dominant laws. The other agents; Agent B, Agent C, Agent D, and Agent E, were given a cropping calendar randomly as we did when all agents had the same laws. We analyzed the number of cropping calendars of all agents except Agent A1 and Agent A2. The simulation results are shown in the bottom row of Table 5.

The number of cropping calendars is Agent E > Agent D > Agent C > Agent B. Closer an agent is to the tail, less irrigation water it gets, and more cropping calendars it produces. The upper row of Table 5 is the number of cropping calendars when all agents have the same laws and the initial Intake Weir inflow. Compared to the same laws, with the different laws Agent D produces four times more cropping calendars and Agent E does three times more. These results show that the existence of the different laws in an area increases cropping calendars of, especially, downstream users when irrigation water is limited.

Table 5: Comparisons of the number of cropping calendars between the same laws and the different laws.

Applied laws	Agent			
	B	C	D	E
The same laws	1	2	2	4
The different laws	1	2	8	11

5 DISCUSSIONS

With Agent-Based Model this study replicated changes in cropping calendars and found two factors of behavioral changes. The field research found that downstream Subaks especially such as Subak D and Subak E varied their cropping calendars every year. The model simulation results are consistent with the field research result, and in the simulation results, downstream agents produced various cropping calendars. Concerning the replication of changes in cropping calendars, this study shows that Agent-Based Model is useful. With Agent-Based Model simulation, this study also found that water resources and the existence of different water use laws were the factors of water use behavior of irrigators in irrigated paddy fields sharing water resources. These results show that ABM simulation can help analyze social and environmental factors of water use behavior.

In Lansing and Kremer model (1993), WUAs synchronized their cropping calendars to reduce pest damage, and their grouping was the optimal way to minimize water stress and increase rice yield. Similarly, in our study area, water stress was a constraint, but pest damage was not farmers' concern so that they didn't have reasons to synchronize their cropping calendars. WUAs were more exposed to the risk of incurring damage stemming from water shortage if water use timing of a WUA was the same with upstream WUAs. Because of these differences, in the prior research two environmental factors defined the water use behavior, and in the level of the whole basins, the WUAs devised their way to adapt to environmental changes. In our study, social and environmental factors were mainly influential to water use behavior, and adaptation methods were developed only among the downstream WUAs.

Although exploring customary laws can reveal factors of current conditions, it does not always let us find solutions for problems or predict future conditions. To examine customary laws on water use we applied game theory. We supposed three values; α, β and γ ($0 \geq \alpha > \beta > \gamma$) showing negative impacts and made a payoff table (Table 6). For Subak B through Subak E, coordinating with other Subaks took efforts and time to arrange water use, but the restrained decline in rice production. On the contrary, disarranging water use saved efforts and time but caused a decline in rice production. From submissive laws, we can see that for farmers decline in rice production ($= \gamma$) is more serious damage than taking efforts and time ($= \beta$). In the case of Subak A, coordinating with other Subaks did not benefit Subak A nor increased rice production, but only took efforts and time. However, uncoordinated water use with the other Subaks yielded the same rice production as it coordinated with the others and took none of the efforts and time, too ($=\alpha$). As Table 6 presents when Subak A is uncooperative and Subak B through Subak E are cooperative, they achieve Nash equilibrium and Pareto optimality. It suggests that with the current customary laws their water allocation system not be changed and uncooperative water use behavior of Subak A not change. This reveals that focusing on one case study will not be enough to find solutions. We can also see that predicting future conditions should be difficult because future changes of externalities cause changes in factors. Therefore, to enhance sustainable resource management, we need to understand what factors and their rules and/or laws are useful to enhance the resilience and adaptability of institutions. However, as prior researchers pointed, although case studies have similarities, to employ rules and/or laws found in other areas to solve problems, we need to carefully tailor them to fit into the target condition (Mukherji *et al.*, 2010). At this point, digital technologies have the potential to facilitate analysis.

Field research results suggested that labor force also influences changes in cropping schedules. Hence, considering rainfall and Saba intake weir inflow is unlikely enough to conduct time series analysis at the current stage of the model development. With further development of digital technologies such as ABM, analysis of time series and massive information in resource management could be conducted. In our study, we found that water resources were the main factor of water users' behavior, but other natural, social and institutional factors also govern their behavior. So far, factors could be divided into three categories; irrigation facilities, cropping systems, and institutions. Irrigation facilities are designed to convey water supply using gravity so that they are influenced by topographical features of an irrigated area. For example, paddy field engineering in Japan has been developed for more than 500 years, and paddy field expansion reached physical limits (The Japanese Society of Irrigation, Drainage and Rural Engineering, 2010). Cropping systems and cropping patterns reflect preferences and strategies of farmers to fit in natural conditions (Corselius et al., 2002 and Dury et al., 2013). Institutions define rules for collective resource use (Ostrom, 2005). This study mainly focused on factors of institutions. To understand and find out robust WUAs, factors in all three categories are needed to consider together. If we accumulate and analyze factors and their rules and/or laws related to resource use in areas of both developing and developed countries, we will be able to grasp the nexus of factors. It will also help us understand how a factor activates another factor(s) and induce rules and/or laws. Understanding resource use behavior in a factor level will enable us to improve resource management by changing some behavior in a more tailored manner. Applying the method of this study to other agricultural resource management needs further research. For instance, agricultural land change may be more influenced by economic change such as land price and market. In such a case, economic models may need to be incorporated into our method.

Table 6: Payoff table between Subak A and Subak B through Subak E.

		Subak B through Subak E	
		Uncooperative	Cooperative
Subak A	Uncooperative	(α, γ)	(α, β)
	Cooperative	(β, γ)	(β, β)

6 CONCLUSIONS

Recently, to improve food and water security, the agriculture sector has attempted to systematize agricultural management which currently mainly relies on farmers' experience. In addition to the challenge, climate change and population growth have made resource management more severe. This questions the sustainability of current resource use by beneficiaries. The prior research shows that water use behavior was subject to environmental factors under limited water resources (Lansing and Kremer, 1993). In consideration of tighter resource availability, it is desirable to examine resource management behavior of beneficiaries using scarce resources to analyze the resilience and adaptability of institutions.

In our study, we studied irrigated rice farmers and analyzed factors of water use behavior of water users' associations in Bali, Subak, to solve the water allocation problem. For analysis, we built ABM by modifying Lansing and Kremer model and simulated water use behavior. The ABM simulations show that ABM can replicate annual changes in cropping schedules which were found downstream WUAs, and water resources and the existence of different water use laws are the factors of water use behavior of irrigators. Therefore, in the study area social and environmental factors were influential to water use behavior, and downstream WUAs developed adaptation methods. Our study shows that digital technologies such as ABM are useful to analyze resource management behavior. To enhance sustainable resource management, ABM also has the potential to analyze factors and their rules and/or laws to understand what enhance resilience and adaptability of institutions. To understand and find out robust WUAs, ABM needs to include more factors related to such as irrigation facilities and cropping systems.

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