FOOD SECURITY IN THE FACE OF CLIMATE CHANGE: ADAPTIVE CAPACITY OF SMALL-SCALE SOCIAL-ECOLOGICAL SYSTEMS TO ENVIRONMENTAL VARIABILITY

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Acknowledgments

We acknowledge Oguzhan Cifdaloz for his help in replicating his Pampa model. Financial support was provided by the National Science Foundation, grant numbers BCS-1115054 and GEO-1115054.

1. Introduction

Increased environmental variability due to climate change is challenging the adaptive capacity of small-scale social-ecological systems. For example, climate change induced rainfall uncertainty can hinder the productivity of small-scale irrigation farming (those of less than 2 hectares in size) which can have profound social and economic consequences (Olesen and Bindi, 2002; Morton, 2007). Those systems, which represent roughly 90% of irrigated lands worldwide, are paramount to address food security, especially in the poorest regions (FAO, 2008). This is particularly relevant for irrigators in Asia, where the monsoon provides the rainfall needed to sustain over 60% of the world's population. Understanding the effects of climate change to small-scale irrigation farming is thus of critical importance. In this study we analyze the capacity of small-scale irrigation systems to adapt to variability in river discharge caused by climate change.

Our study is motivated by the Pampa irrigation system, a small-scale irrigation system located in Nepal that is a model for this class of agricultural systems: relatively long-lived, small-scale irrigation and well adapted to historical regular variability in water resources. Climate change projections suggest that historical water conditions may change significantly and seriously affect irrigators. The complex spatiotemporal behavior of the Asian monsoon generates high levels of uncertainty which limits confidence concerning the projections about the behavior of the Asian monsoon to climate change (Turner and Annamalai, 2012; Kitoh et al., 2013). Given that uncertainty, here we use an agent-based model that captures the essential features of the Pampa irrigation system to study the performance of small-scale rice paddy systems under different projections of climate change in the region. Those projections include changes in the water supply (i.e. increase or decrease in rainfall), variation in river discharge distribution (i.e. reduction and expansion of the monsoon season), and temporal shifts in river discharge (i.e. early and late monsoon onset).

Agent-based modeling enables us to study the consequences of the interactions of multiple individual entities (e.g. farmers) for the larger scale system (e.g. productivity of the whole community). The model aims to capture both the biophysical (e.g. resource dynamics) and social dynamics (e.g. individual decisions) as well as the coupled social-ecological interactions (e.g. individual decisions change based on the information or status of the ecological system which then feed back into and subsequently change the ecological system) (Janssen and Ostrom, 2006). In the model developed here, the biophysical condition of interest is the level of water flow in the river under different climate change scenarios simulated during the summer irrigation season. The social dynamics simulated in our model include the farmers' decisions about which irrigation strategy to use and their coordination efforts. The social-ecological interactions come from the farmers' decisions based on the availability of the resource. Farmers in the Pampa system use four types of irrigation strategies based on the amount of water flow in the river. When water is plentiful, it is distributed on a continuous flow basis from upstream to downstream irrigators. During periods of water scarcity, farmers can supply water to sectors sequentially or, if water is scarce during the sensitive mid-season, sectors are supplied with water on 12 hour rotations or, when water is extremely scarce, in 24 hour rotations (Cifdaloz et al. 2010).

Based on ethnographic fieldwork, Cifdaloz et al. (2010) used a differential equation model of the Pampa irrigation system to analyze how well-tuned farmers' institutional arrangements are to the biophysical context and their flexibility to cope with resource variability caused by reduction in water discharge and delay in the monsoon season. They concluded that farmers in the Pampa System are selecting irrigation strategies that are consistent with those that are most efficient in each situation of water scarcity in the model. Although, Cifdaloz et al. (2010) model was a simplification of the Pampa irrigation system, it was empirically grounded using ethnographic observations and Nepalese irrigation experts. Their work was a first step in analyzing the adaptive capacity of small-scale farmers to climate change. In the work presented here, we build on the work of Cifdaloz et al. (2010) by adding five features to the model: i) agents' capacity to make decisions and adapt their irrigation strategy to the external conditions of water availability, ii) a greater range of climate change scenarios based on recent regional climate change projections on the Asian monsoon, iii) resource uncertainty caused by a wash out of the main water diversion structures due to an increase in the water flow, iv) farmers' coordination challenges under climate change, and v) the interlinked effects of the temporal shift, water discharge change and water distribution scenarios.

Specifically, instead of analyzing the performance of each irrigation strategy independently as in Cifdaloz et al. (2010), here sectors must decide every time step which irrigation strategy to use based on the water flow available. In addition, while Cifdaloz et al. (2010) only considered two climate change scenarios (rainfall reduction and late monsoon onset), we analyze the capacity of farmers to cope with water variability caused by the projected impacts of climate change on the Asian monsoon including both an increase and decrease in rainfall, reduction and expansion of the monsoon season, and early or late monsoon onset. Uncertainty is introduced in our model (Cifdaloz et al.'s model did not explicitly include uncertainty) by including a probability of a wash out of the main water diversion structures that will reduce water available and will require cooperation among farmers to repair it. Although farmers have knowledge of the distribution of past disturbances to which they have adapted, to capture the effects of climate change we assume that the distribution of disturbances is unknown to the farmers in the model. Next, we exploit the strengths of the agent-based approach, to measure the total yield of the system, explore yield inequality among the agents within the system, clarify the potential coordination challenges that climate change might pose to farmers, and attempt to unravel the interlinked effects of the different climate change scenarios.

Although our model is a theoretical exercise of the effects of climate change on the monsoon and the adaptive capacity of irrigation farmers, the model we extend is empirically grounded. Further, the climate change scenarios are based on recent data on monsoon behavior, namely, the monsoon is arriving later with more variable rainfall events (Indian Meteorological Department). While Cifdaloz et al. (2010) model was designed to understand if farmers are choosing the most efficient irrigation strategies given the water availability they face, here, by including the extensions to Cifdaloz et al.'s model mentioned above, we are able to generate hypotheses about the most sensitive scenarios for irrigation farming in terms of yield, inequality and coordination challenges and to discuss some possible solutions and trade-offs in the process of adaptation. Considering the limitation of our modelling exercise in terms of simplification of reality, our simulations show that rainfall intensification, significant reduction in rainfall, and changes in the monsoon onset might, as we might expect, have disastrous effects on small-scale irrigation in

Nepal. The simulations highlight more subtle social-ecological interactions in which climate change forces farmers to increase their level of coordination to obtain some yield in the system but the irrigation strategies used by farmers in such circumstances may lead to high levels of inequality among farmers. Thus, although the model suggests that investment in new infrastructure might increase the performance of the system under a range of climate change scenarios, the social consequence manifest in the high inequality among farmers when water availability is low might hinder the efficiency of these measures due to a reduction of farmers' willingness to cooperate.

2. Methods

Here we provide details of how we developed and used an agent-based model to attempt to gain some insights into how small-scale resource systems may or may not be able to cope with challenges associated with climate-change. The model presented here, builds on an empirically grounded model of the Pampa irrigation system in Nepal (Cifdaloz et al. 2010). In this section, we describe the basic biophysical features of the system, irrigation strategies, the basic model features, and the climate scenarios we test.

2.1. *The Pampa irrigation system*

The Pampa irrigation system is located in Chitwan, in the Central Region of Nepal. Chitwan, one of the 75 districts in Nepal, is located 150 km south of Kathmandu, covers 2218 Km² and is predominantly agricultural. The Pampa Khola river flows north-south and the associated irrigation system is managed by the local farmers. The irrigation system under study is located in Birendranagar village and serves 140 households who own 70 hectares of agricultural land. Seventy-five percent of households own between 0.3 to 0.7 hectares of land and landholdings range from 0.2 to 3 hectares. The Pampa is one of 125 farmer managed irrigation systems (FMIS) located in Chitwan. Water diversion is decided by the irrigator community. The command area of the Pampa is divided into six sectors, each covering approximately 12 hectares, and composed by 18 to 28 households. The most important crops in the region are paddy rice during monsoon season and either maize or wheat in winter. Here we focus on monsoon paddy as it is the most important crop in the region. For a more detailed description of the study system readers are referred to Cifdaloz et al. (2010).

2.2. *River regime and irrigation stages*

Paddy cultivation activities are closely timed with the monsoon cycle. From June to August the area receives most of its annual rainfall. Mean monthly discharge ranges from 0.75 m³/s in the driest month of April to 15.44 m³/s in the wettest month of August (Fig. 1). Water discharge can vary widely from year to year. The maximum and minimum recorded discharge in April and August in the Pampa are 0.2 m³/s and 35 m³/s, respectively (Nippon Koei Company Ltd., 1986).

The beginning of the cropping calendar for monsoon paddy falls between May 15 and June 23. The cropping cycle is usually 4-5 months and ends with harvesting by the end of October. The

cultivation process comprises four stages: field preparation and transplant, vegetative, mid-season (reproductive stage), and late season (ripening stage) (Fig. 1).

Before transplantation, a nursery seed bed is prepared. Seeds are sown sometime between May 15 and June 23 and become ready for transplantation about a month later. The sanding water requirement during this period is on average 20 mm. Preparation of the fields requires three to four weeks for flooding, ploughing, puddling, and leveling the soil before rice can be transplanted. This process requires about 200 mm of standing water. After the seedlings are transplanted, the standing water level is maintained at 100 mm. During the latter part of the vegetative stage, the water level is reduced to 20-50 mm and then increased again during the mid-season stage. Water demand for paddy cultivation is summarized in Fig. 1.

The most sensitive and least sensitive stages to water shortages are the mid-season and late season, respectively. The mid-season is the most sensitive of the stages to water shortages, stem elongation and flowering occurs. If the plant does not receive adequate water during this stage, it affects rice yields significantly (see below). On the contrary, the least sensitive stage is the late season, when rice is reaching maturity. During this last stage, rice water needs are at a minimum and water is actually cut off to the fields 10-15 days before the harvest.

<<FIGURE 1 ABOUT HERE>>

2.3. Water institution and irrigation strategies

The “irrigation community” is defined by the shared institutions used to decide the rules-in-use governing water diversion and distribution. The irrigation rules included in our model are based on the ethnographic work presented by Cifdaloz et al. (2010). Water distribution can take a number of forms. When water is plentiful, it is distributed on a continuous flow basis with upstream irrigators having prior use rights over downstream irrigators. During periods of scarcity, there are two distinct allocation schemes: one for the transplantation phase and one for the mid-season.

During scarce periods in the transplantation phase, water is supplied sequentially to the sectors: all of the flow is diverted to sector 1, then to sector 2, and so on. During the mid-season, the irrigation community recognizes two levels of scarcity: moderate and severe. Under moderate scarcity, each sector is supplied water only for 12 hours. This rotation translates into each sector taking a turn to irrigate every fourth day. However, when water is extremely scarce, each sector receives water for 24 hours every seventh day. Simulation results by Cifdaloz et al. (2010) concluded that farmers in the Pampa are selecting strategies that are consistent with model predictions for the most efficient in each situation of water scarcity.

2.4. Model description

The model presented here is a modification of the original Pampa model developed by Cifdaloz et al. (2010) based on differential equations. Perez et al. (2013) carefully replicated that original model using an agent based modeling approach which is publicly available and fully documented at <http://www.openabm.org/model/3580/version/1>. Here, we further extend this

agent-based version by giving agents (i.e. sectors in the irrigation system) the capacity to make decisions and adapt their irrigation strategy to the external conditions of water availability. Thus, instead of analyzing the performance of each irrigation strategy independently as in Cifdaloz et al., (2010), here sectors must decide every time step which irrigation strategy to use based on the water flow available. This modification allows us to investigate how well the system will perform under different climate change projections in terms of yield, inequality, and coordination among farmers as well as the interlinked effects of water discharge change, temporal shift, and water distribution scenarios.

Agents in our model also face resource uncertainty caused by a wash out of the main water diversion structures due to an increase in the water flow. Given this stochasticity, we run 100 simulations of each climate scenario (see below) of one year long at a daily time step. In what follows, we provide a basic description of how the model works and the decisions agents make. A more detailed description of the model following the ODD (overview, design concepts, and details) protocol for describing individual and agent-based models (Grimm et al., 2006; Grimm and Railsback, 2005; Grimm et al., 2010) as well as the model code are available at <http://www.openabm.org/model/3981/version/1/view>. The model is implemented in NetLogo v.5.0 (Wilensky, 1999; <http://ccl.northwestern.edu/netlogo/>).

Every day water flows through the canals. The water available to irrigate depends on the climatic scenarios considered (described in detail below). Within these scenarios we analyze the capacity of agents to adapt depending on: i) how much water is available to irrigate (water scarcity), ii) when in the planting cycle water scarcity occurs, and iii) when an increase of water flow in the main river may cause a wash out of the main water diversion structures.

Depending on the amount of water available, the six sectors together select the irrigation strategy that will be used. As mentioned before, the Pampa irrigation system uses four irrigation policies: open flow, sequential, 12-hour rotation and 24-hour rotation. The modeling work of Cifdaloz et al. (2010) suggested that under ordinary operating conditions, the optimal strategy is open flow (minimum labor requirements). The model showed that when water scarcity increases beyond a certain threshold, the irrigators should switch to a sequential water distribution strategy. Both of these predicted strategies are consistent with what is observed in the field (Cifdaloz et al., 2010). Finally, the model showed that under specific conditions of high water scarcity associated with a wash out of the main headgate infrastructure, irrigators should use a 12-hour rotation if the time needed to repair the infrastructure is low (5 days) or a 24-hour rotation if this time is large (8 days). Again, the model predictions match the field observations based on the interviews with farmers as presented by Cifdaloz et al. (2010). Traditionally, washouts in the Pampa happen during the mid-season of the irrigation period, when the peak of monsoon season occurs. Thus, Cifdaloz et al. (2010) simulated the performance of the 12 and 24-hour rotation strategies during the mid-season. However, a temporal shift of the monsoon season due to climate change may shift the period of highest probability of a washout to other irrigation stages. Thus, we give agents the capacity to change the irrigation strategy whenever a washout happens and not only the ability to use the 12-hour or 24-hour rotation strategies during the mid-season. Previous simulations showed that results are similar with both strategies because the main effect of the washout is during the five-eight days when water flow is zero. Here we don't consider water loss in the canals due to leaking based on the findings of Cifdaloz et al. (2010) which showed that

although leakage can have a significant effect on irrigation performance in general, it likely had no effect on irrigation strategies in the Pampa system in particular.

2.5. Climatic scenarios

The possible impacts of climate change on the South Asian monsoon include an increase in the frequency of drought and flood periods, an increase or decrease in the amount of rainfall, as well as a temporal shift of the monsoon season (Table 1). However, there is a high uncertainty about the behavior of Asian monsoon related to climate change (Turner and Annamalai, 2012). Most of the projections show an increase in monsoon rainfall and just a few show drier conditions (Ashfaq et al., 2009) (see Table 1). Fewer studies are available about the timing of the monsoon season, and it is not clear if changes in the amount of rainfall will be associated with a reduction or expansion of the monsoon season (Ashfaq et al., 2009; Kitoh et al., 2013). In addition, most of these models have a limited confidence on their projections (Kitoh et al., 2013).

Considering this uncertainty, we explore three possible scenarios of impacts of climate change on our study area: i) changes in the water supply (i.e. increase or decrease in rainfall), ii) variation in river discharge distribution (i.e. reduction and expansion of the monsoon season), and iii) temporal shifts in river discharge (Fig. 2). These scenarios include all the projections made about the impacts of climate change on South Asian monsoon (Table 1).

<<TABLE 1 ABOUT HERE >>

In relation to the first scenario, Cifdaloz et al. (2010) analyzed the effects of lower river flows during monsoons. Here, since most of the monsoon projections show an increase in rainfall and a few projections a decrease, we model both situations. For the second scenario, we analyze the effect of changes in the water discharge regime during monsoons. First, we adjusted the water river discharge used by Cifdaloz et al. (2010) to a normal distribution with mean in 235 days and standard deviation of 35 (i.e., the best fit to the normal distribution). We then simulated the effect of different river discharge regimes by changing the value of the standard deviation a range between -25 and +25 (Fig. 2). The water discharges obtained is within the range of the maximum and minimum recorded water discharge in the Pampa (Nippon Koei Company Ltd., 1986). Finally, we modeled the temporal shift of monsoon season (third scenario) by reducing and increasing the mean value of the normal distribution from -45 to +45 days (Fig. 2).

<<FIGURE 2 ABOUT HERE >>

In addition, water diversion structures and gates are routinely washed out during the monsoon season at Pampa (Regmi, 2008). Thus, an increase in water flow may cause an increase in the probability of water infrastructures to fail. This is included in the model by introducing a sigmoidal function relating the probability of irrigation infrastructure failing to water discharge volume (Fig. 3).

<<FIGURE 3 ABOUT HERE >>

2.6. Performance of the system

Performance is measured by means of the total yield obtained by the six sectors as well as the Gini coefficient of yield among sectors. After irrigating the land, yield is calculated based on the water level of each sector. Sufficient water means that the water level remains within the bounds shown in Fig. 1. If a drought occurs the actual water level will fall outside the desired band, causing water stress. The longer the drought, the longer the actual water level will remain outside the band. The yields are penalized depending on the cumulative water stress. The cumulative water stress is computed as the area between the actual and the desired water height (Fig. 1). The impact of a drought on the yield differs depending on the stage of the growth cycle. Field preparation and midseason stages are relatively more critical than the vegetative stage and late season (Fig. 4, see the mathematical function in <http://www.openabm.org/model/3981/version/1/view>).

<<FIGURE 4 ABOUT HERE >>

In addition to changes in yield and equality among farmers, climate change may challenge the coordination of farmers in terms of infrastructure repair, meetings, decisions, etc. We used the number of times farmers need to switch from one irrigation strategy to another as a proxy for the coordination effort of farmers. If conditions are optimum, farmers will use the open strategy during the whole irrigation season and thus the value of this coordination indicator will be zero (i.e. number of switches is zero).

3. Results

Here we present results of 100 simulations of our agent-based model for each scenario of climate change (changes in water discharge, changes in the water supply distribution and temporal shift in the monsoon season). Fig. 5 shows the frequency in which each irrigation strategy is selected by farmers in the different climate change scenarios considered. Fig. 6 to 8 show the performance of the system (average and standard deviation of total yield and inequality among irrigation sectors) for the climatic scenarios simulated, and Fig. 9 shows the interlinked effect of the three climate change scenarios simulated. We use the number of times farmers switch between irrigation strategies as represented in Fig. 5 as a proxy of the coordination challenges of farmers.

3.1. Changes in water discharge

As Fig. 6 shows, the system is very robust to water discharge reductions of up to 50%. The system can get up to 100% of the maximum total yield. These results are consistent with Cifdaloz et al. (2010). Variability is caused by a washout in the water diversion structures during the mid-season, when the peak water flow occurs. If the washout needs more than 5 days to be repair, it increases the inequality among farmers, because agents select the 24-hours rotation strategy, which increases the total yield by allowing at least sectors one and two to get enough water to produce rice but it results in downstream sectors producing a total yield of almost 0 (Fig. 6). When the water discharge reduction is lower than 50%, farmers use the open flow strategy during the whole irrigation season unless a washout in the water diversion structures

occurs. In those circumstances, farmers switch from the open flow to the 12 or 24-hours rotation strategy (Fig. 5, first row, all but first column). When reductions in water supply are higher than 50%, total yield drops sharply. Farmers use the sequential strategy and switch to a 12 or 24-hour rotation strategy if a washout in the water diversion structures happens (Fig. 5, first row, first column). Again, in those situations farmers, by using the 24-hours rotation, are allowing only upstream sectors to get enough water to produce rice (Fig. 6).

<<FIGURES 5 and 6 ABOUT HERE>>

3.2. Changes in the water supply distribution

Fig. 7 shows the performance of the system for different distributions in the water supply (Fig. 2). The system is very sensitive to an increase in the temporal concentration of water flow. When the standard deviation of the water (sd) is under 25, the system suffers a reduction of 100-67% in the total yield. With this water flow distribution, water scarcity occurs during the most sensitive stages of the irrigation season (stages one and three) (Fig. 1 and 4). During stage one, water flow is almost zero, and during stage three there is a high probability of suffering a washout in the water diversion structures that causes an important water scarcity.

Under these circumstances, agents use the sequential strategy during the stage one of the growth cycle. When water scarcity decreases during the second stage they switch to an open flow strategy. Agents will use the open flow if irrigation infrastructure is well maintained but if diversion structures are washed out they will use the 12-hour or 24-hour rotation strategy (Fig. 5, second row, first column). A washout causes an important decrease in the total yield because it will affect stage three of the irrigation period. When the infrastructure is recovered, they will switch again to an open flow until they use the sequential strategy at the end of stage three when water scarcity will be high again due to a decrease in the water flow (Fig. 5, second row, first column). Within this water distribution the inequality among sectors is very high. Only sectors one and two are able to get enough water to produce rice (Fig. 7). A particular situation with $sd = 23$ causes a rapid decrease in the total yield because a significant water scarcity occurs during stage three of the irrigation season (Fig. 7).

When the sd of the water increases to between 25 and the regular situation ($sd=35$), the yield is 100% for the six irrigation sectors (Fig. 7). Agents use an open flow strategy until they switch to a 12-hour or 24-hour rotation strategy if a washout in the water diversion infrastructures (Fig. 5, second row, second and third columns). However, a washout does not have an important effect on the total yield because it happens during the stage two and the structure is recovered soon enough to not suffer water scarcity during stage three. Within this water distribution the inequality among irrigation sectors is zero (Fig. 7).

A wider distribution in the water flow causes an increase in the variability of the total yield (Fig. 7). This is caused by an increase in the uncertainty about a possible washout in the water diversion structures. With more concentrated water distribution the uncertainty about occurring a washout was very low because the probability of a washout is close to one (Fig. 3). When rainfall intensity decreases, our simulations predict that it is more difficult for the systems to recover from a washout due to water scarcity during the recovery period, causing an increase in

the variability of the total yield (Fig. 7). It is with this water distribution that the difference in performance between five or eight days needed to repair the irrigation infrastructures are more marked. When the sd is close to 40, a washout will affect with higher probability the most sensitive days of the third stage of the irrigation season, causing an important reduction in the total yield. Sectors use an open flow strategy that would result in a 100% yield if the infrastructure doesn't fail. However, if the infrastructure fails, irrigators will use the 12-hour rotation or 24-hour rotation (Fig. 5, second row, fourth and last columns).

<<FIGURE 7 ABOUT HERE >>

3.3. Temporal shift in the monsoon season

Fig. 8 shows four main periods with different performance levels that resulted from the time shift scenario. These periods depend if the water scarcity occurs during the most or less sensitive stages of the irrigation season (stages one and three, or two and four respectively) (Fig. 2 and 4).

When the monsoon season starts very early (24 or more days earlier), the system might not reach the maximum total yield. In this situation, water scarcity occurs during the first stage of the irrigation season caused by a washout in the diversion structures. If the irrigation infrastructures are well maintained, the system may reach a maximum level of total yield. Initially, agents use the open flow strategy until they switch to the 12 hour or 24 hour rotation strategy when a washout happens. This shift can happen in the first or second stage of the irrigation season (Fig. 5, third row, first column). Lower total yields are obtained when the washout happen in the first stage of the irrigation season due to its sensitivity to water scarcity. This would happen with a higher probability as the monsoon season starts earlier. When the water diversion structures are recovered, farmers switch back to the open flow strategy (Fig. 5, third row, first column). Water scarcity suffered at the end of the irrigation period made farmers to switch to a sequential strategy (Fig. 5, third row, first column). It is important to notice that in those situations simulations predicted a very low inequality levels among sectors (Fig. 8).

If the monsoon season starts 25 or fewer days earlier, yield reaches 100% (Fig. 8). In this situation, water is not scarce during stages one and three and a washout in the water diversion structures may occur during stage two, when the system doesn't need an important water inflow. Agents use an open flow strategy until a washout happens. Once the diversion structure has been repaired, irrigators switch back to the open flow strategy (Fig. 5, third row, second and third column).

The sensitivity of the system increases when the monsoon season starts late. If monsoon season starts less than 30 days later, the total yield may decrease to up to 10% and the inequality between sectors would be high (Fig. 8). In this situation water scarcity is due to a washout of the diversion structures during stage three. Agents use the open flow strategy until the diversion structure is washed out during the third stage of the irrigation season (Fig. 5, third row, fourth column). Since stage three is very sensitive to water scarcity, a washout causes an important decrease in the total yield. When the infrastructures are recovered, they switch back to the open flow strategy (Fig. 5, third row, fourth column). If washout does not happen, farmers continue

using the open flow strategy and a maximum total yield is obtained (Fig. 5, third row, fourth column).

Finally, the system is most sensitive when monsoon season starts 30 or more days later (Fig. 8). In this situation, the water flow is very low during the first stage of the irrigation system but a washout won't have an important effect because it would happen during the four stage of the irrigation season. Initially, agents use the sequential strategy, then they switch to the open flow when water scarcity decreases until a washout in the water diversion structures made them switch to the 12-hour or 24-hour rotation strategy. Once the infrastructures are recovered, they switch back to the open flow strategy (Fig. 5, third row, last column). A particular situation happens when the time shift is 26 days. In this situation, the washout affects the initial days of stage three, causing an important decrease in the total yield (Fig. 8).

<<FIGURE 8 ABOUT HERE >>

3.4. Farmers' coordination under climate change

In normal conditions, the farmers need to change the irrigation strategy up to two times (Fig. 5). This switch of strategies is caused by a washout in the water diversion structures, thus farmers switch from the open flow to the 12 hour or 24 hour rotation strategy (Fig. 5, e.g. second and third columns). However, with some climate change scenarios farmers need to change up to four times the irrigation strategy (Fig. 5, e.g. second row, first column).

In the river discharge change scenario higher coordination problems occur with a river discharge reduction of more than 50%, precisely when the total yield decreases to 0 and the inequality among farmers is very high (Fig. 5, first row, first column).

In the water discharge distribution change scenario, farmers need to change up to four times the irrigation strategy to just maintain a total yield below the 40% when the rainfall is very concentrated ($sd < 20$) (Fig. 5, second row, first column). However, when the concentration of the rainfall is very low, farmers only need to use the open flow irrigation strategy if a washout does not occur (Fig. 5) (Fig. 5, second row, fourth and last columns).

Finally, in the time shift scenario, farmers need to increase their coordination effort to maintain a total yield of more than 60% when the monsoon season start very early (40 days) (Fig. 5, third row, first column). In a climate scenario of very late monsoon season (40 days), farmers need to change three times the irrigation strategy each season to maintain a low total yield (less than 30%) and a high inequality among farmers (Fig. 5, third row, last column).

3.5. Interlinked effects of the temporal shift, water discharge change and water distribution scenarios

Here we analyze how our system responds to changes in the water flow distribution in conjunction with a time shift in the monsoon season and water discharge change. Fig. 9 represents the water discharge change scenarios for two different values of the standard deviation

of the water distribution in an early (Fig. 9, first row), normal (Fig. 9, second row), and late (Fig. 9, last row) monsoon onset.

Changes in the rainfall intensification have an important impact on the total yield of the system in all scenarios for monsoon arrival time shift (Fig. 9, first and second columns), while the time shift in the monsoon system seems to have an effect on the system only in situation in which the rainfall is concentrated in a few days during summer (Fig. 9, first and second rows).

<<FIGURE 9 ABOUT HERE >>

4. Discussion and conclusion

In this study we used an agent-based model to analyze the performance of small-scale irrigation systems under different scenarios of water discharge, water distribution and rainfall onset changes in the Asian monsoon caused by climate change. We used the Pampa irrigation system in Nepal as a model of small-scale irrigation systems and build on the empirically grounded model developed by Cifdaloz et al (2010). According to our simulations, certain empirically grounded scenarios for impacts of climate change on the behavior of the Asian monsoon might have a disastrous effect on agriculture in Nepal. Our simulations also show that irrigation institutions seem to be robust to: rainfall increases, small decreases of rainfall, small expansion of monsoon length and early onset but very vulnerable to: rainfall intensification, high rainfall reductions, late onset or very early onset of the monsoon.

Considering the most probable scenarios of climate change on the Asian monsoon (rainfall increase, rainfall intensification, and earlier/later onset) (Table 1), our simulations suggest that farmers will need to adapt to rainfall intensification and a late onset, given the sensitivity of the irrigation system to these scenarios. Based on our simulations, under those scenarios, the performance of the system will be reduced due to a higher probability of a washout in the main water diversion structures. In response, farmers might need to invest more resources in the improvement and maintenance of the irrigation infrastructure. However, under those situations the irrigation strategies currently used by farmers in the Pampa irrigation system are able to maintain a certain level of yield by increasing the inequality among farmers. When a washout occurs, farmers use the 12 hour or 24 hour rotation strategy (based on Cifdaloz et al. 2010 ethnographic data) that, accordingly to our simulations, in most of the cases, only allows for two of the six farmers, depending on how the rotation is begun, to have a successful crop. Behavioral experiments using an irrigation game showed that, downstream participants are less willing to invest than upstream participants, and that downstream participants' investment in the public irrigation infrastructure decreases as the inequality among participants increases (Baggio et al., 2015; Pérez et al., 2015). Thus, we might expect that cooperation of farmers to maintain the irrigation infrastructure in the Pampa might be hindered due to higher levels of inequality. Our simulations suggest that this reduction of cooperation among farmers might worsen because the conditions which require more coordination coincide with those in which more inequality is observed. The results of our modeling exercise suggest that, under unfavorable climatic conditions, farmers might need to invest more in coordination (e.g. infrastructure repair,

meetings, decisions, etc.) in order to adapt to new water flow conditions but they might not be able to maintain high yield levels in the system or equal distribution of the rice production.

However, it is important to highlight that our analysis, as with all modeling exercises, is based on a simplification of reality. Our model relies on a number of assumptions which may have considerable effects on the results of the simulations but are difficult, if not impossible, to predict. For example, the headgate infrastructure breakdown relies on estimated probabilities for which we have only ethnographic observational data. Other factors such as migration, innovation, or cultivation of other products than paddy rice were not included in our model.

Here, we have focused on the adaptation capacity of farmers in small-scale irrigation systems to water discharge changes caused by climate change. The results of our model allowed us to explore the most sensitive scenarios for irrigation farming in Nepal and to discuss some possible solutions and trade-offs in the process of adaptation. Farmer-managed irrigation systems (FMIS), such as the one that inspired the model developed here, substantially contribute to the agricultural production in Nepal as they constitute around 39% of the total irrigation area in Nepal (Bhandari and Pokharel, 1998). Climate change is just one element of a very complex set of problems faced by rural communities such as aging farmers, migration, or isolation from global markets (Jones and Boyd, 2011; Kiem and Austin, 2013). Among these many problems, although climate change may not even be the most important, at a minimum it will add stress that these systems can ill afford to bear. Improving the adaptive capacity of small-scale irrigation farmers to the impacts of climate change impacts on the Asian monsoon is crucial for food and water security in Asia. Bearing in mind the limitations of the assumptions discussed above, our modeling exercise does provide some general policy insight. Specifically, very careful attention to how coordination among farmers and infrastructure maintenance interact under specific climate change scenarios is critical to improving the performance of small-scale irrigation systems and, in turn, food security in Nepal.

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Table 1. Recent projections of the impact of climate change on South Asian monsoon (June-September). Symbols: • = no change; → = late; ← = early; ↑ = increase; ↓ = decrease ; * = predictions in Central Nepal.

Fig. 1. Desired water level (i.e., demand) and water supply (river regime). Blue line=mean discharge, red line=desired level, gray polygon=desired supply level range.

Fig. 2. Climatic scenarios simulated. A) Variation in river discharge, B) variation in river discharge temporal distribution, C) temporal shifts in river discharge. The red line represents the simulated normal distribution from original data (mean = 235, sd= 35). The blueish lines show the minimum, maximum, as well as some intermediate values of the variables changed in each climate change scenario simulated.

Fig. 3. Probability of headgate infrastructure break. The red line is the simulated normal distribution from original data (mean = 235, sd= 35) and the color gradient represents changes in the standard deviation of the normal distribution.

Fig. 4. Performance measure coefficient functions for droughts for the four irrigation stages. The most sensitive stages to drought conditions are the field preparation and transplant (stage one) and reproductive (stage three) stages and the less sensitive are the vegetative (stage two) and ripening (stage four) stages.

Fig. 5. Frequency of the selected irrigation strategies in each time step for the 100 runs for different instances of the climate change scenarios. First row: River discharge change (rate of increase or decrease of the water flow), second row: Water distribution change (measured as different standard deviation of the normal distribution of rainfall), and third row: Time shift (early [negative days] and late [positive days] onset). The column in the middle shows the scenario under no climate change (river discharge = 100%, normal distribution of rainfall with mean = 235 and standard deviation= 35, and time shift = 0 days). Different colors indicate the irrigation strategy: Orange= open flow, purple= sequential, green= 12 or 24 hour rotation.

Fig. 6. Average total yield and average cumulative Gini coefficient of 100 runs as a function of water discharge change rate with five (left) and eight (right) days needed to repair the irrigation infrastructure. The light gray represents the standard deviation. The red dotted line is the simulated normal distribution from original data (mean = 235, sd= 35).

Fig. 7. Average total yield and average cumulative Gini coefficient of 100 runs as a function of water discharge distribution with five (left) and eight (right) days needed to repair the irrigation infrastructure. The light gray represents the standard deviation. The red dotted line represent the simulated normal distribution from original data (mean = 235, sd= 35).

Fig. 8. Average total yield and average cumulative Gini coefficient of 100 runs as a function of time shift in river discharge with five (left) and eight (right) days needed to repair the irrigation infrastructure. The light gray represents the standard deviation. The red dotted line is the simulated normal distribution from original data (mean = 235, sd= 35).

Fig. 9. Average total yield of 100 runs as a function of both time shift in river discharge and water discharge distribution under different river discharge rates. The light gray represents the standard deviation. Rows represent changes in the rainfall intensification while columns represent changes in the onset. Figure shows that changes in the rainfall intensification reduces the total yield of the system in all scenarios of changes in the onset, while the time shift in the monsoon system seems to have an effect on the system only in situation in which the rainfall is concentrated in a few days.

Table 1. Recent projections of the impact of climate change on South Asian monsoon (June-September). Symbols: • = no change; → = late; ← = early; ↑ = increase; ↓ = decrease ; * = predictions in Central Nepal.

	Impact	Projection / Scenario	Region	Trend	Magnitude	Source
Rainfall	Rainfall	-	South Asia	↓	-	Annamalai et al., 2013
	Rainfall (%)	Double CO ₂	Indian subcontinent	↑	5–25	Annamalai et al., 2007
	Rainfall	Double CO ₂	South Asia	↓	-	Ashfaq et al., 2009
	Change ratio in averaged precipitation (%)	RCP4.5 and RCP8.5	South Asia	↑	7-13	Kitoh et al., 2013
	Change in monthly precipitation (%)	2030s	Central Nepal	↑	5*	NCVST, 2009
		2060s		↑	10*	
		2090s		↑	19*	
	Mean summer precipitation projections (mm d ⁻¹)	Double CO ₂	South Asia	↑	0.4-0.6	Turner and Annamalai, 2012
Rainfall intensity	Simple precipitation daily intensity index	RCP4.5 and RCP8.5	South Asia	↑	7-15	Kitoh et al., 2013
	Seasonal maximum 5 day precipitation total			↑	11-22	
	Change in precipitation as heavy events (%)	2060s	Central Nepal	↑	4*	NCVST, 2009
		2090s		↑	8*	
	Onset	Onset date (pentad)	Double CO ₂	South	→	1-2*
Onset date (days)		RCP4.5 and RCP8.5			←, •	~(-5)
Retreat	Retreat date (days)		South Asia	→	~5-7	
Duration	Duration (days)		South Asia	↑	~7-16	

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9