Hydrological Sciences Journal

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/thsj20

Water management for irrigation, crop yield and social attitudes: a socio-agricultural agent-based model to explore a collective action problem

Lucia Tamburino , Giuliano Di Baldassarre & Giulia Vico

HYDROLOGICAL SCIENCES JOURNAL
2020, VOL. 65, NO. 11, 1815–1829
https://doi.org/10.1080/02626667.2020.1769103

SPECIAL ISSUE: ADVANCING SOCIO-HYDROLOGY

Water management for irrigation, crop yield and social attitudes: a socio-agricultural agent-based model to explore a collective action problem

Lucia Tamburino [a], Giuliano Di Baldassarre [b,c] and Giulia Vico [a]

[a]Department of Crop Production Ecology, Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden; [b]Department of Earth Science, Uppsala University, Uppsala, Sweden; [c]Centre of Natural Hazards and Disaster Sciences (CNDS), Sweden

ABSTRACT
When rainfall does not meet crop water requirements, supplemental irrigation is needed to maintain productivity. On-farm ponds can prevent excessive groundwater exploitation – to the benefit of the whole community – but they reduce the cultivated area and require investments by each farmer. Thus, choosing the source of water for irrigation (groundwater *vs* on-farm pond) is a problem of collective action. An agent-based model is developed to simulate a smallholder farming system; the farmers' long-/short-view orientation determines the choice of the water source. We identify the most beneficial water source for economic gain and its stability, and how it can change across communities and under future climate scenarios. By using on-farm ponds, long-view-oriented farmers provide collective advantages but have individual advantages only under extreme climates; a tragedy of the commons is always possible. Changes in farmers' attitudes (and hence sources of water) based on previous experiences can worsen the economic outcome.

ARTICLE HISTORY
Received 12 June 2019
Accepted 7 April 2020

EDITOR
S. Archfield

GUEST EDITOR
S. Pande

KEYWORDS
agent-based model; precipitation unpredictability; collective action; supplemental irrigation; groundwater; on-farm ponds; crop yield

1 Introduction

In many regions, rainfall does not reliably meet crop water requirements – a condition that could be exacerbated by climate change (IPCC 2014). Farmers are faced with the challenge of maintaining and possibly increasing agricultural production under water scarcity. The risk of failing this challenge is high, not only due to current and future climatic conditions but also as the result of human response, which can be inefficient or consist of short-term solutions that can backfire in the long run (e.g. Kahneman 2011, Schill *et al.* 2019). For instance, the need for supplemental irrigation has already led to groundwater over-exploitation in many regions, resulting in a decline of water tables (El-Naqa *et al.* 2007, Scanlon *et al.* 2012, Wada *et al.* 2012). In some cases, what appears the most appropriate solution is not applied due to other factors (e.g. Bussmann *et al.* 2016), thus calling for the implementation of specific policies and incentives. This situation can trigger a vicious circle of ecological fragility-economic poverty (Cheng *et al.* 2019). Towards a more sustainable and climate-resilient agriculture, we thus need to explore the implications of different management choices for crop production, resource use, and economic viability, explicitly including the human dimension of decision-making under uncertainty.

Models provide a powerful tool to investigate the interactions between environmental conditions and human response to them. To be effective, modelling approaches need to explicitly combine environmental dynamics with human behaviour. One of the most common approaches to represent human behaviour is based on the theory of expected utility. Albeit classical in economy, this theory neglects individual attitudes and traits. It is based on assumptions – such as rational actor and perfect information – that are often in contrast with empirical observations of how people actually make decisions and behave under uncertainty, in particular when dealing with natural resource use (Van den Bergh *et al.* 2000). Thus, alternative theories have been proposed, such as bounded rationality, prospect theory, descriptive norm (Kahneman and Tversky 1979, Cialdini *et al.* 1991, Schlüter *et al.* 2017). Within agriculture, an early attempt to consider individual attitudes in decision-making processes was based on categorizing farmers as analytical and intuitive (Öhlmér *et al.* 1998). Choosing different traits (e.g. risk aversion, memory, imitation), different categorizations are possible. In the spirit of socio-hydrology (Sivapalan *et al.* 2012, Di Baldassarre *et al.* 2013, Viglione *et al.* 2014), some models of human-agriculture systems have been recently proposed (Pande and Savenije 2016, den Besten *et al.* 2016, O'Keeffe *et al.* 2018). These models were based on the observed behaviour of smallholders and farmers in India and quantified the impact of water use behaviour on crop production and farmer livelihoods. In a similar vein, a stylized model for smallholders in Kenya was recently developed, incorporating perceptions regarding water availability on crop choice and water allocation (Kuil *et al.* 2018).

Water harvesting techniques, such as on-farm ponds, provide an alternative to groundwater as a source of water for irrigation. On-farm ponds can collect water when it is abundant and be used as a source of water for irrigation during dry spells. Their use is widespread and promoted in many regions (e.g. Bouldin *et al.* 2004, Palanisami *et al.* 2010, NRAA 2013, Rao *et al.* 2017,

CONTACT Giulia Vico giulia.vico@slu.se Department of Crop Production Ecology, Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden
Supplemental data for this article can be accessed here.

Acheampong *et al.* 2018). On-farm ponds are often a more sustainable source of water than groundwater at least locally. They can reduce the water table decline (Sikka *et al.* 2018) and provide a wide range of ecosystem services (Bouldin *et al.* 2004, Moore and Hunt 2012, Céréghino *et al.* 2014, Omer and Baker 2019). At the same time, the use of on-farms ponds implies some tradeoffs. At the farm level, they require a large initial investment by the farmer and reduce the cultivated area. Hence, they imply advantages for the whole community, by preserving groundwater resources, but not for the single farmer who chooses to build a pond. This typical situation arises in the management of common resources. It falls within the definition of collective action problem, namely a situation where individuals face choices "in which the maximization of short-term self-interest yields outcomes leaving all participants worse off than feasible alternatives" (Ostrom 1998, p. 1).

There is an increasing interest in the role of collective action to improve the effectiveness of natural resource use in rural areas (OECD 2013, Zavalloni *et al.* 2018). Nevertheless, despite the big potential to mitigate the effects of dry spells in a sustainable way, the use of on-farm ponds has seldom been evaluated as a problem of collective action and included in socio-agricultural models (van Valkengoed and Steg 2019).

To fill this knowledge gap, we developed a novel agent-based model simulating a smallholder farming system, where crops, water resources and humans interact under conditions of water scarcity and unpredictable rainfall occurrence. Supplemental irrigation can be obtained either from the underlining aquifer only or via the integration of on-farm ponds with groundwater. The farmer's attitude towards sustainable behaviours is explicitly considered, by categorizing the farmer according to their long/short-term orientation. This trait corresponds to one of the social dimensions in the Hofstede's cultural dimensions theory (Hofstede 1991, 2011), and drives the role of farmers in collective action. We use the model to explore under which climatic conditions and in which communities the use of on-farm ponds as an additional source of irrigation water is beneficial in terms of net economic gain and its stability, for the single farmer and the whole community.

While the model was maintained as simple as possible to ensure general applicability, it was calibrated for the case of the Lower Mississippi River Basin (USA). In this region, the water table has been declining sharply, mainly due to irrigation withdrawals (Reba *et al.* 2017, Yaeger *et al.* 2018) and the use of water from on-farm ponds is encouraged and increasing (USDA NRCS 2014, Omer and Baker 2019, Omer *et al.* 2019).

The remainder of the paper is organized as follows: Section 2 describes the model, from the general idea (Section 2.1) to the specific equations (Section 2.2) and their parameterization (Section 2.3 and Supplementary Online Material). Section 3 contains the results of the model simulations along with a discussion. Conclusions are presented in Section 4.

2 Methods

2.1 Conceptual model

We developed an agent-based model simulating a smallholder farming system (Fig. 1), under conditions of water scarcity and unpredictable rainfall. We consider a community of N farmers, each managing a farmland of extension A_{farm}. The farmers in the community derive their income from the crop they grow on their farm. The crop yield attained every year depends on

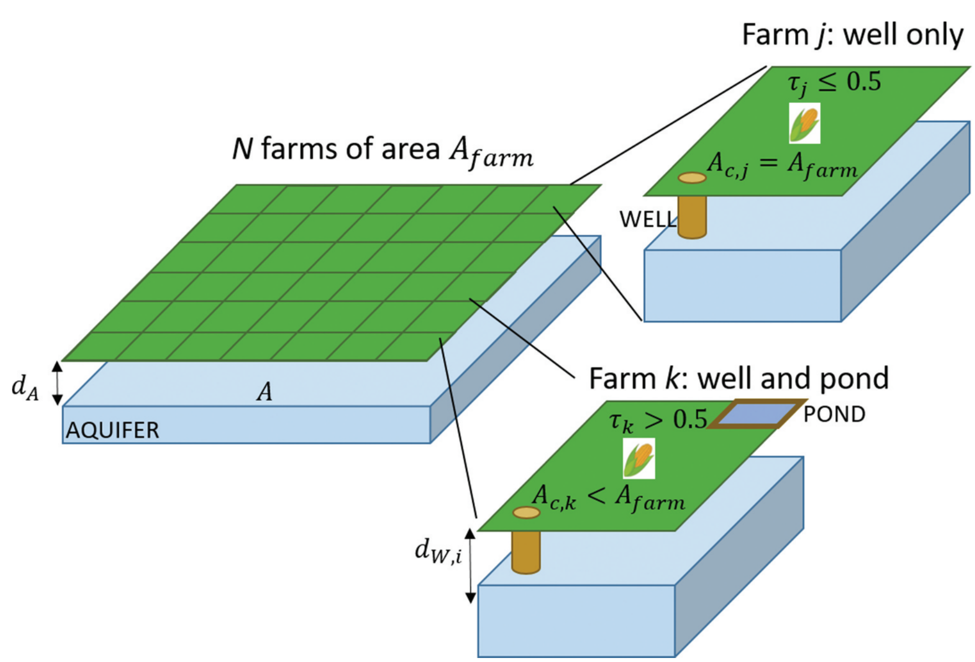

Figure 1. Schematic representation of the system modelled. The farmed land (top) sits on the aquifer A and is divided into patches (squares), each representing a farm. The farmers (one for patch) are the agents, making strategic decisions relative to their farm. Farms are of the same size (A_{farm}), but the cultivated area can differ from farm to farm, depending on whether the farmer has invested in an on-farm pond or not. Two farms with contrasting features are presented on the right. In farm j, the farmer is short-view oriented ($\tau_j < 0.5$), hence relies only on groundwater for irrigation and can cultivate the entire farm. In farm k, the farmer is long-view oriented ($\tau_k > 0.5$), hence invested in an on-farm pond (blue square), which occupies a part of the farm, thus reducing the cultivated area $A_{c,k}$.

the extension of the cultivated area and on the occurrence of crop water stress (i.e. the plant soil water availability during the growing season). The inputs to the soil water balance are rainfall, represented in the model as a stochastic process, and irrigation applications.

Farmers can choose the source of water for irrigation, depending on their own attitudes. They can: i) use only groundwater, accessing it through a well; or ii) choose to invest also in on-farm ponds to store water during the non-growing season, when water is abundant. In the latter case, they take water from the ponds and resort to groundwater only when the pond becomes empty. The on-farm pond reduces the amount of cultivated area from A_{farm} to A_c and requires a large initial investment, but lasts longer than a well to access groundwater. The pond is assumed to be refilled to capacity every year during the non-growing season thanks to rainfall and runoff or inputs from superficial waterbodies (Prince Czarnecki *et al.* 2016). A well for groundwater extraction is generally cheaper than the construction of an on-farm pond, but groundwater recharge can be extremely slow, so that the water table can deepen over time, to the point that the existing well is no longer be able to reach the water table. A deeper well can be dug, but its construction requires a new investment of money and time. This means that, if the water table becomes too deep during the growing season, groundwater cannot be accessed for the rest of the season. Moreover, the costs associated with well construction increase with depth, so that, eventually, a well can become more expensive than a pond.

The farmer's choice of the source of water for irrigation depends on their attitude and on the available economic resources. For each farmer i, the attitude is driven by the long/short-term orientation of the farmer summarized by the parameter τ_i, ranging from 0 to 1. Values of τ_i below a threshold (here set in the middle of the range, i.e. at 0.5) lead farmers to rely only on groundwater (short-view-oriented farmers); values above the threshold lead them to invest in a more sustainable irrigation source, i.e. the on-farm pond, as a complementary source of water (long-view-oriented farmers). Nevertheless, τ_i (and hence the farmer's long/short-view orientation) can change over time depending on the events (here, the attained crop yield in the previous years) and the farmer's (fading) memory of them. If the value of τ_i crosses 0.5, the farmer changes their attitude and hence the source of water for irrigation, for example, deciding to invest in an on-farm pond when τ_i becomes greater than 0.5.

We aim to explore how the crop yield and the net economic gain, both total and per capita, and the depth of the water table, evolve over time depending on the climate conditions and the farmers' attitude.

2.2 Model design

The system, schematically presented in Fig. 1, evolves based on the equations in discrete time steps described below. Time is represented as a sequence of ticks, which are divided into two subgroups: growing season and non-growing season. For simplicity, we assumed that farms are all identical in terms of size and pedoclimatic conditions, since the total area is small. All the farmers are endowed with the same initial capital and sow the same crop.

2.2.1 Growing season

In each farm, crop growth is simulated through a system of equations to be interpreted at the daily timescale, coupling the temporal evolution of crop biomass, b_i, and plant water availability in the soil, w_i (Vico and Porporato 2013). Rainfall R is represented as a stochastic process, thus explicitly including its variability and unpredictability.

2.2.1.1 Plant water availability. The variable w_i represents the soil water available to the plants, i.e. the amount of water stored within the active rooting depth that can be taken up by the crop (volume per unit ground area, i.e. a depth). At each time step, the plant available water is determined by the balance between inputs via precipitation R and irrigation I (if any), and losses via evapotranspiration ET and superficial runoff and deep percolation (Rodriguez-Iturbe *et al.* 1999):

$$w_i(t) = \min\left(w_1, w_i(t-1) + R(t) + \frac{I_i(t-1)}{A_{c,i}} - \mathrm{ET}_i(w_i(t-1)) \cdot \Delta t\right) \quad (1)$$

where $A_{c,i}$ represents the cultivated area of the farm and Δt represents a time tick in the growing season. While rainfall is the same for all the farms, irrigation can change from farm to farm, depending on water availability; and different irrigation amounts can result in different ET losses. Therefore each farm i has its own plant available water w_i, irrigation input I_i and losses via evapotranspiration, ET_i.

To facilitate the exploration of different climate scenarios, precipitation R is artificially generated. To this aim, precipitation occurrence is idealized as a marked Poisson process. Intervals between two rainfall events are exponentially distributed, with mean frequency λ (d^{-1}). Event depths are also exponentially distributed, with mean α (m).

A demand-based irrigation strategy is considered (Vico and Porporato 2011). An irrigation application occurs when plant available water decreases below a threshold $\tilde{w}$ (intervention point). A pre-set level $\hat{w}$ is restored, provided that there is enough available water a_i stored in the on-farm pond or accessible via the irrigation well, depending on the chosen source for water irrigation. The applied irrigation volume in the ith farm I_i can be hence written as:

$$I_i(w_i, a_i) = \begin{cases} \min\left(a_i, A_{c,i}(\hat{w} - w_i)\right) & \text{if} \quad w_i \le \tilde{w} \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

where a_i is estimated as per Equations (8)–(10) below.

The evapotranspiration rate depends on several environmental variables and crop features, chiefly air temperature and humidity, solar radiation and wind speed, stomatal conductance, leaf size, and transpiring biomass. The evapotranspiration rate in the ith farm, ET_i, is assumed to change during the growing season, as a result of the seasonal changes in temperature and solar radiation, as well as with plant water availability. Specifically, ET_i is a piecewise-linear function of w_i, increasing from zero when no water is available to the plants ($w_i = 0$) to a maximum rate of $\mathrm{ET}_{\max}$ at w^* (Laio *et al.* 2001). Below this value, transpiration rate is reduced as:

$$\mathrm{ET}_i(w_i) = \begin{cases} \frac{\mathrm{ET}_{\max}}{w^*} w_i & \text{if } \mathrm{w_i} \le \mathrm{w}^* \\ \mathrm{ET}_{\max} & \text{otherwise} \end{cases} \tag{3}$$

where w^* is the level of soil plant availability corresponding to the incipient stomatal closure and $\mathrm{ET}_{\max}$ is the evapotranspiration rate under well-watered conditions (see the Supplementary Material, Section S1.2 for details).

Finally, losses via surface runoff and deep percolation are assumed to occur instantaneously whenever w_i reaches a threshold w_1 (hence the minimum function in Equation (1)). w_1 depends on the plant active rooting depth and the soil texture. By avoiding the high nonlinearities injected by the dependence of the soil hydraulic conductivity on the soil volumetric water content (e.g. Campbell 1974), this simplified representation of the surface runoff and deep percolation is amenable for a solution of Equation (1) with Δt = 1 d, without introducing significant numerical errors.

Based on Equation (1), w_i ranges between 0, when no water is available for plant uptake (i.e. at soil water potentials corresponding to the plant wilting point), and w_1. w_i can be linked to soil saturation level (described in the Supplementary Material, Equation (S1)).

2.2.1.2 Crop development and yield. The farm marketable yield is determined based on the total crop biomass in the farm at the end of the main growing season (i.e. soon after flowering for most crops), $b_i(t_{\mathrm{seas}})$, as $Y_i(t) = \mathrm{HI} b_i(t_{\mathrm{seas}})$, where HI is the harvest index (e.g. Hay 1995, Evans and Fischer 1999).

In turn, and in line with observations (e.g. Cavero *et al.* 2000, Heggenstaller *et al.* 2009, Feng *et al.* 2019, Song *et al.* 2019), the total crop biomass b in each farm grows exponentially during the main growing season, with rate g, i.e. (Vico and Porporato 2013),

$$b_i(t) = b_i(t-1) + g_i(w_i(t-1)) \cdot b_i(t-1) \cdot \Delta t \tag{4}$$

The function g_i represents the relative growth rate. It is assumed here that the relative growth rate (and hence final yield) can be reduced only by water shortage, i.e. no other limitations to crop development are implemented. As such, g_i depends on soil water availability: when water is scarce, carbon fixation is reduced, with negative impacts on plant ability to produce new biomass; under severe water scarcity, the total biomass can even diminish, since the plants can die. A piecewise linear function is assumed to describe the dependence of g_i on w_i:

$$g_i(w_i) = \begin{cases} -\beta + \frac{g_{\max}+\beta}{w^*} w_i & \text{if } \mathrm{w_i} \le \mathrm{w}^* \\ g_{\max} & \text{otherwise} \end{cases} \tag{5}$$

where $g_{\max}$ is the maximum relative growth rate (d^{-1}), corresponding to well-watered conditions and β (d^{-1}) is a biomass deterioration rate. The threshold w^* is the same plant available water below which ET decreases, given the close relation between plant transpiration and carbon fixation at the leaf level.

The cultivated area, $A_{c,i}$, does not appear explicitly in the definition of the total farm biomass (Equation (4)), but affects the initial condition and hence the total biomass and final yield. Specifically, $b_i(1) = B\,A_{c,i}$, where B is the amount of initial crop per unit of surface (kg m^{-2}). B can be interpreted as the mass of seeds planted in a square metre.

2.2.1.3 Available irrigation water. The water for irrigation can be obtained from an on-farm pond or from the aquifer. If the farm has a pond, its water level $d_{P,i}$ evolves during the growing season as driven by irrigation withdrawals within the single farm in which it is located:

$$d_{P,i}(t) = d_{P,i}(t-1) - \frac{I_i(t-1)}{\mathrm{A_{farm}} - A_{c,i}} \tag{6}$$

where $A_{\mathrm{farm}} - A_{c,i}$ is the area of the on-farm pond, i.e. the complement of the cultivated area $A_{c,i}$ in the farm. The water in the pond could also increase due to runoff collected from the fields, rainfall falling directly on the pond, and other off-farm surface waterbodies; and decline via evaporation. However, these contributions are not considered here. Neglecting the within-season recharge via runoff or other surface waterbodies allows focusing on the worst-case and most sustainable scenario, where the regional water balance during the period of peak water demand remains unaffected by the use of on-farm ponds. Furthermore, during the growing season rainfall falling directly on the pond and evaporation tend to compensate each other (Prince Czarnecki *et al.* 2016).

Also, the water table depth d_A accessible to *all* farmers evolves during the growing season as a result of the water withdrawals of *all* the farmers in the community who use groundwater for irrigation, i.e.

$$d_A(t) = d_A(t-1) + \frac{1}{A}\sum_i I_i \tag{7}$$

Here A represents the aquifer surface, I_i is the irrigation applied by the *ith* farmer and the index i varies in the set of all farmers who are using groundwater at time t. For simplicity, no groundwater recharge is included, so that the results below represent the worst-case scenario.

Now it is possible to define a_i, i.e. the water volume available for irrigation (Equation (2)), depending on the source of water and the features of the available infrastructures. The contribution to irrigation from the on-farm pond is:

$$a_{P,i}(t) = \begin{cases} d_{P,i}(t) \cdot \left(A_{\mathrm{farm}} - A_{c,i}\right) & \text{if } \mathrm{A_{c,i}} > 0 \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

where the second case corresponds to the absence of the on-farm pond. Conversely, the potential contribution of groundwater:

$$a_{w,i}(t) = \begin{cases} A \cdot \left(d_{w,i} - d_A\right) & \text{if } \mathrm{d_{w,i}} > \mathrm{d_A} \\ 0 & \text{otherwise} \end{cases} \tag{9}$$

where $d_{w,i}$ is the maximum depth of the water table accessible via the existing pumping infrastructure currently available in the farm. If the water table is deeper than the well, the groundwater is no longer accessible and therefore unavailable to the farmer. Finally, considering that in a farm where there is a pond, water for irrigation is obtained from the pond till the pond is empty ($d_{P,i} = 0$), and from the groundwater after that, while the only source of water is the groundwater where there is not a pond, the volume available for irrigation, at any time t in the ith farm, $a_i(t)$, is given by:

$$a_i(t) = \begin{cases} a_{P,i}(t) \text{ if } \mathrm{a_{P,i}(t)} > 0 \\ a_{W,i}(t) \text{ otherwise} \end{cases} \quad (10)$$

2.2.2 Non-growing season

During the non-growing season, the farmers' irrigation infrastructure, economic status, and attitude (i.e. short/long-view orientation and memory) are updated depending on the crop yield obtained during the previous growing season and the status of the infrastructure itself. Depending on the values of the attitude parameter τ_i and the available funds, management actions can then be implemented in the farm, thus potentially altering the farm infrastructure and initial water availability during the subsequent growing season. Note that, in the equations used in the non-growing season routines, time refers to years, i.e. they are to be interpreted at a different timescale from that used for the equations relative to the growing season.

2.2.2.1 Irrigation infrastructure. The irrigation infrastructure can be improved during the non-growing season, provided the farmer has enough funds to support the associated investments. For example, when a pump breaks down or the well is no longer deep enough to reach the water table, a farmer can replace it with a new one. The depth of new wells is set based on the current depth of the aquifer. Moreover, a farmer relying only on groundwater can decide to build the on-farm pond. Once built, the pond is kept until the end of its lifespan. Then, the farmer can decide whether to build it again or to use groundwater only for supplemental irrigation, thus recovering the entire arable land.

Furthermore, during the non-growing season, on-farm ponds, if present, are refilled. For simplicity, we assume that the pond is fully recharged during the non-growing season, because, in general, the season is long, and it is characterized by low losses via evapotranspiration and direct evaporation, so that collected runoff and discharge of other surface waterbodies are potentially large.

2.2.2.2 Economy. The ith farmer's capital, $E_i(t)$, is the net result of revenues and expenses:

$$E_i(t) = E_i(t-1) + c \cdot Y_i(t) - O_i(t) \quad (11)$$

The revenues in a given year depend on the crop price, c, and the attained marketable yield $Y_i(t)$. In each year, the costs O_i are given by the sum of two terms: (i) a fixed cost, which is the same for all the farmers and does not depend on the extension of cultivated area (e.g. investment and maintenance of tractors and other machines); and (ii) the aggregated expenses stemming directly from the cultivation activities (e.g. the cost of seeds), and hence dependent on the cultivated area in the farm $A_{c,i}$. (see Supplementary Material, Section S3.1 for details). A further cost is added to these two terms if, after updating the attitude parameters and after the farmer's decision, a new well or pond is built. Hence, these additional costs are greater than zero only when the water table becomes too deep and a new groundwater extraction infrastructure is needed; when the pump breaks down and needs a replacement; or when the pond is at the end of its lifespan and needs replacement. Maintenance costs for pumps and ponds are not considered; rather, the model accounts for their functional deterioration over time, leading to the need for replacement. In the case of the groundwater extraction infrastructure, deterioration implies that it can fail and need replacement with a probability linearly increasing with its age, independently of the water table depth. Conversely, ponds have a finite lifespan (see Supplementary Material, Section S3.1).

2.2.2.3 Farmers' attitude: short-/long-view orientation and memory of previous outcomes. Irrigation choice is driven by the farmer's attitudinal parameter τ_i, representing their short/long-view orientation: long-view-oriented farmers ($\tau > 0.5$) will cooperate to avoid an over-exploitation of the common resource by building a pond for supplemental irrigation, while short-view oriented farmers ($\tau \leq 0.5$) will focus only on their immediate economic gain, using exclusively groundwater. We summarize the initial composition of the whole community as the proportion of short-view to long-view-oriented farmers (SOF-ratio), i.e. the ratio of farmers initially using only groundwater and farmers complementing the groundwater extraction infrastructure with on-farm ponds.

For each farmer, the attitude parameter τ_i is assumed to change depending on the events and on how the farmer remembers them, according to the following equation:

$$\tau_i(t) = \tau_{0,i} \cdot M_i(t) \quad (12)$$

Here $\tau_{0,i}$ represents the initial value of the farmer's attitude (randomly attributed but respecting the SOF-ratio of the community simulated) and $M_i(t)$ is the memory of the past outcomes. More specifically, we assume that the farmer remembers the ratio between the attained yield in a year $Y_i(t)$ and a desired yield $\hat{Y}$. The desired yield $\hat{Y}$ is assumed to correspond to the 80% of the maximum attainable yield, i.e. the yield obtained when well-watered conditions can be maintained throughout the growing season. This ratio is indicative of whether a year has been a good year ($Y_i(t)/\hat{Y} > 1$), a neutral year ($Y_i(t)/\hat{Y} = 1$), or a bad one ($Y_i(t)/\hat{Y} < 1$) for the farmer. We assume that the memory $M_i(t)$ accumulates over the years with a decay rate μ ranging between 0 and 1 – another attitude parameter of the farmer (Di Baldassarre *et al.* 2017). Hence, the ith farmer's memory $M_i(t)$ evolves in time as:

$$M_i(t) = \mu \frac{Y_i(t)}{\hat{Y}} + (1-\mu) M_i(t-1) \quad (13)$$

with the initial condition set to $M_i(1) = \frac{Y_i(1)}{\hat{Y}}$. It follows that a sequence of neutral years implies that $M_i = 1$ and thus does not change the value of the attitude parameters τ_i. Conversely, sequences where good (bad) years prevail lead to values of M_i larger (smaller) than 1 and as such an increase (decrease) of both M_i and τ_i. The rationale is that, under good conditions, humans tend to become more long-view-oriented, while negative conditions lead to more short-view orientations and risk-taking attitudes (Kahneman and Tversky 1979, Scholer *et al.* 2010, Kahneman 2011). A decay rate $\mu = 0$ corresponds to the case of constant farmers' attitude parameter τ_i and hence constant SOF-ratio in the community. Given the uncertainty regarding the parameter μ we consider both the case of constant τ_i (setting $\mu = 0$) and that in which it evolves with $\mu = 0.2$.

Once the attitude parameter τ_i is defined based on the current and previous years, the farmer makes their decision on the irrigation system according to the scheme in Fig. 2. Depending on the value of the parameter τ_i, the farmers choose their source of water for irrigation: only groundwater for $\tau_i \leq 0.5$; or, when they are more oriented towards sustainable choices (i.e. long-view-oriented; $\tau_i > 0.5$), on-farm pond and groundwater (farm j and k, respectively, in Fig. 1). Note that changes in the value of τ_i result in a change of the farmer's behaviour (and hence the source of water for irrigation) only when the value crosses the threshold 0.5. After the decision, the farmer's economy is updated, including any possible expense for the construction of an on-farm pond.

2.3 Model parameterization and simulations

While of general applicability, the model is here calibrated for the case of the Lower Mississippi River Basin (USA). The parameterization is presented and justified in detail in the Supplementary Material. In short, we consider corn grown over sandy loam, with the main growing season running from 25 April to 4 July. A stress-avoidance irrigation is considered (i.e. $\widetilde{w} = w^*$). Current climate conditions (ET_{max}, λ and α) were determined based on observed meteorological conditions in the region. To explore the effect of future, warmer and more extreme climates, we further varied the climatic parameters, reducing the total average precipitation by 20% and 50% and increasing air temperature by 2°C and 4°C (and hence ET_{max}) to define an "intermediate" and "extreme" climate scenario, respectively (Table S2). We simulated a community of $N = 121$ farmers, each managing an area $A_{farm} = 3.5$ ha. Regarding the irrigation infrastructure, all farmers have a well. At construction, the depth of a new well exceeds that of the water table at that time of a depth $\Delta d_W = 0.75$ m. Those that also employ an on-farm pond as a source of irrigation water, have a pond covering 8% of the farm area, which is comparable to the current local guidelines (USDA 1982, Ouyang *et al.* 2016) and to the size that would ensure the highest production under current climates (Vico *et al.* 2020). Different community composition in terms of initial short- and long-view-oriented farmers (i.e. SOF-ratios) are explored.

The model is initialized as follows: At the beginning of each growing season, the soil is assumed to be at the point of incipient stomatal closure; and the pond, if any, filled to capacity (i.e. $d_{P,i} = 2$ m). We performed 100 simulations for each parameter combination. Each simulation lasts 30 years, i.e. is based on 30 time series of daily precipitation with parameters λ and α. Unless otherwise specified (Fig. 7), the initial water table depth was $d_A = 5$ m. In all cases, the initial well depth was $d_{W,i} = d_A + \Delta d_W$. Each farmer had an initial capital equal to twice the cost of building an on-farm pond.

3 Results and discussion

First, we consider the case of constant attitude parameter τ_i (i.e. $\mu = 0$ and hence $\tau_i = \tau_{0,i}$ throughout the simulation). We show (a) a comparison of yields and net economic gains

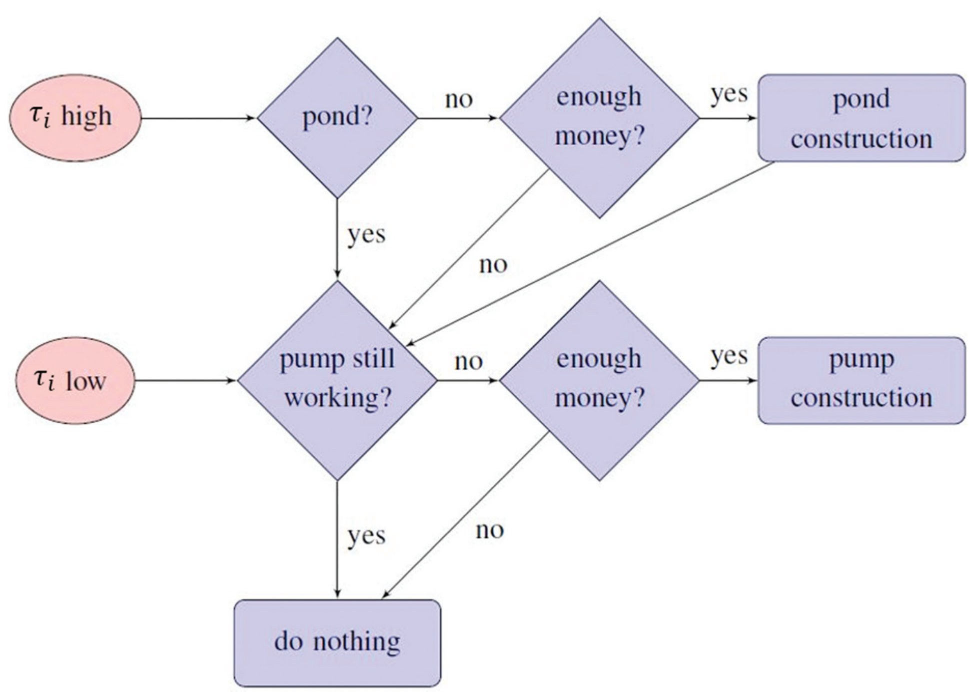

Figure 2. The farmer's decision-making process for the irrigation source. The farmer's attitude parameter τ_i is compared with a threshold: when $\tau_i > 0.5$, the farmer is considered long-view-oriented and aims to rely also on the on-farm pond for irrigation; otherwise, the farmer is considered short-view-oriented and willing to rely only on groundwater for irrigation.

between short *vs* long-view-oriented farmers belonging to the same community, under different climate scenarios (see Section 3.1); (b) a comparison of the average net economic gain among communities characterized by different proportions of short-view to long-view-oriented farmers (i.e. differing in SOF-ratio; Section 3.2). In the latter case, we also explore the role of different initial conditions for the water table depth. Finally, we consider the case of single farmer's attitude parameter τ_i evolving in time, as the result of previous experiences (i.e. $\mu > 0$), and examine how the community composition and the net economic gain are affected by the initial community composition under different climates (Section 3.3).

3.1 Role of orientation on single farmers' outcomes in different communities

Figure 3 shows the temporal evolution of the final crop biomass and water table depth of two farmers, belonging to the same community but differing in their orientation (short-view vs. long-view). The farmer's orientation does not evolve in time. Different communities are considered (panels), from one dominated by long-view-oriented farmers (low SOF-ratio), to a mixed one (SOF-ratio of 0.5), to two dominated by short-viewed farmers (high SOF-ratios).

Farmers relying only on groundwater (i.e. short-view-oriented farmers; dashed red lines) achieve higher yields, as long as they can access water with their well, because the cultivated area is larger. Nevertheless, they experience bad years, i.e. years with sharp reductions in yields, when the water table becomes too deep to be reached by the existing well. Note that even the long-view-oriented farmer experiences low-yield years (solid green line) when the water table falls below the depth of the well, as the on-farm pond alone does not contain enough water to perform a stress-avoidance irrigation under dry conditions over the entire growing season. However, such yield reductions are generally less sharp than for short-view-oriented farmers, because the use of the water stored in the pond mitigates water scarcity. Long-oriented farmers have hence lower but more stable crop yields and economic gains. The frequency of bad years increases with the SOF-ratio, as a high SOF-ratio leads to a faster use of the groundwater and consequently to a faster decline of the water table.

In all communities, the water table declines approximately linearly with time (Fig. 3, blue lines), but at a faster rate in communities with higher SOF (see Fig. 5 for more detail). Also, the average wells become deeper and deeper, to follow the decline in the water table (Fig. 3, purple line). While, in

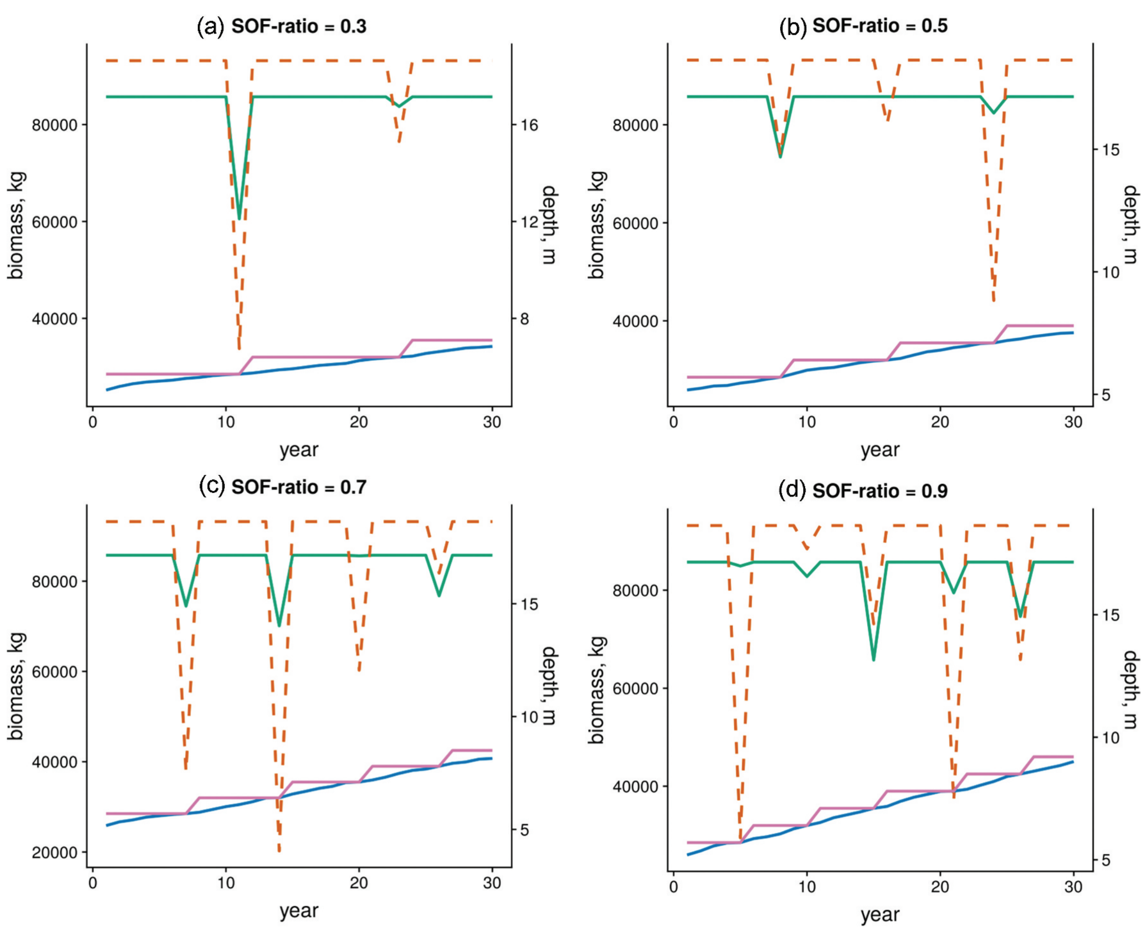

Figure 3. Temporal evolution of final crop biomass, water table and well depths in a 20-year sample model run, for four communities differing in their SOF-ratio. Dashed red lines refer to crop-biomass achieved by a short-view-oriented farmer, solid green lines to that achieved by a long-view-oriented farmer; in blue the depth of the water table and in purple the average depth of the wells. For enhanced visibility of the differences across communities and farmers, here the climatic conditions correspond to the extreme climate scenario, but similar patterns emerge also for more moderate scenarios. The farmers' attitude does not evolve in time (i.e. $\mu = 0$).

principle, each farm could have wells of different depth (the result of different pump breakdown times and different choices), in most cases a new well is dug in response to a decline in water table depth and hence the variability across farms is limited.

Figure 4 explores the effect of climatic conditions. There, the average net economic gain over 30 years of the long-view and short-view-oriented farmers are plotted against the community SOF-ratio, for the three climate scenarios, assuming that the single farmer's attitude does not evolve in time.

For the current and intermediate climates (Fig. 4(a) and (b)), short-view-oriented farmers are wealthier than long-view-oriented ones, regardless of the community composition. Nevertheless, their economic gain is less stable, with the exception of the current climate in communities with SOF-ratio smaller than 0.25. From the point of view of a single farmer, the most profitable

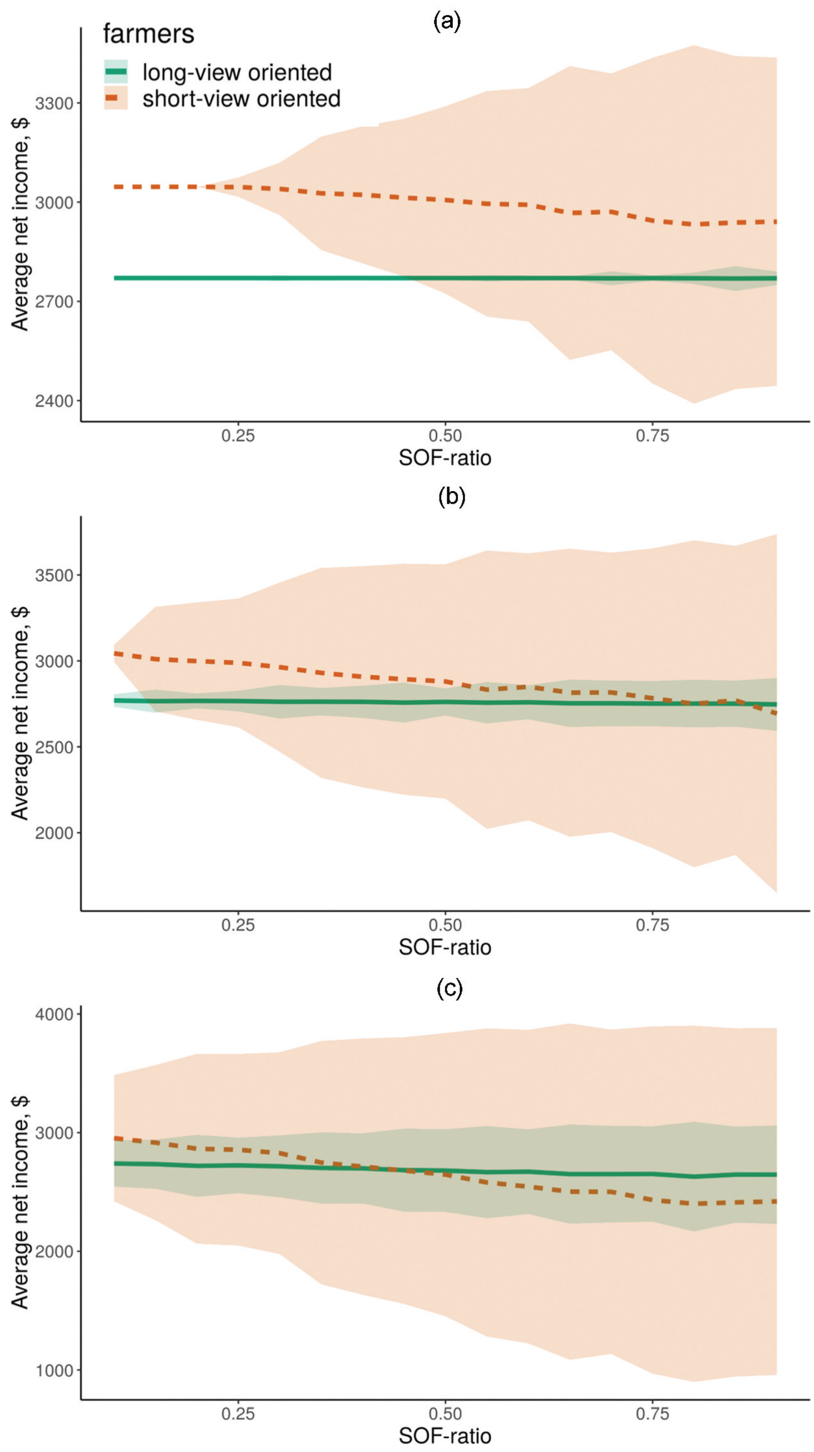

Figure 4. Average net economic gains over 30 years for long-view-(green solid line) and short-view-(red dashed line) oriented farmers, as a function of the SOF-ratio, under three different climate scenarios: a) current, b) intermediate, and c)extreme climate. Shaded areas extend over the average plus and minus the standard deviation. The farmers' attitude does not evolve in time (i.e. $\mu = 0$).

situation is to be short-viewed in a community with a majority of long-view-oriented farmers (i.e. low SOF-ratio). This is a common outcome when there is a shared resource to manage (Ostrom *et al.* 1999). In contrast, under the extreme climate scenario (Fig. 4(c)), being long-view-oriented leads not only to more stable yields (and hence economic gains) regardless of the community SOF-ratio but also to higher average net economic gains for SOF-ratios greater than 0.45.

3.2 Whole community outcomes

Figures 5 and 6 show, respectively, the depth of the water table after 10 and 20 years and the average net economic gain over a period of 30 years under the different climate scenarios, in communities with different (but constant in time) SOF-ratios.

The water table level declines faster in communities with a high SOF-ratio, due to the more extensive use of

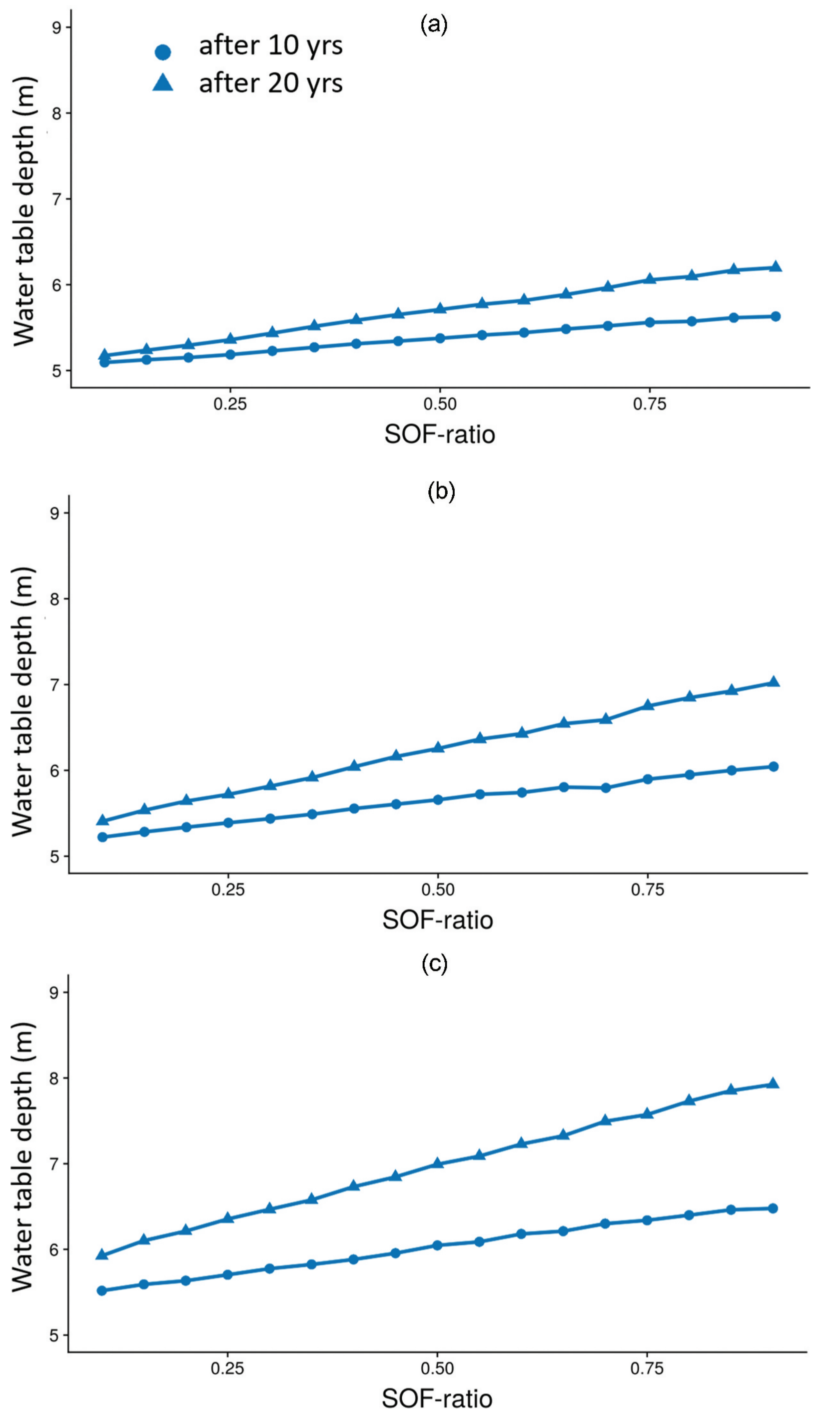

Figure 5. Water table depths, averaged over 100 simulations, in communities differing in SOF-ratio after 10 (circles) and 20 (triangles) years, with a starting water table depth of 5 m: (a) current climate, (b) intermediate climate and (c) drier climate. The farmers' attitude does not evolve in time (i.e. $\mu = 0$).

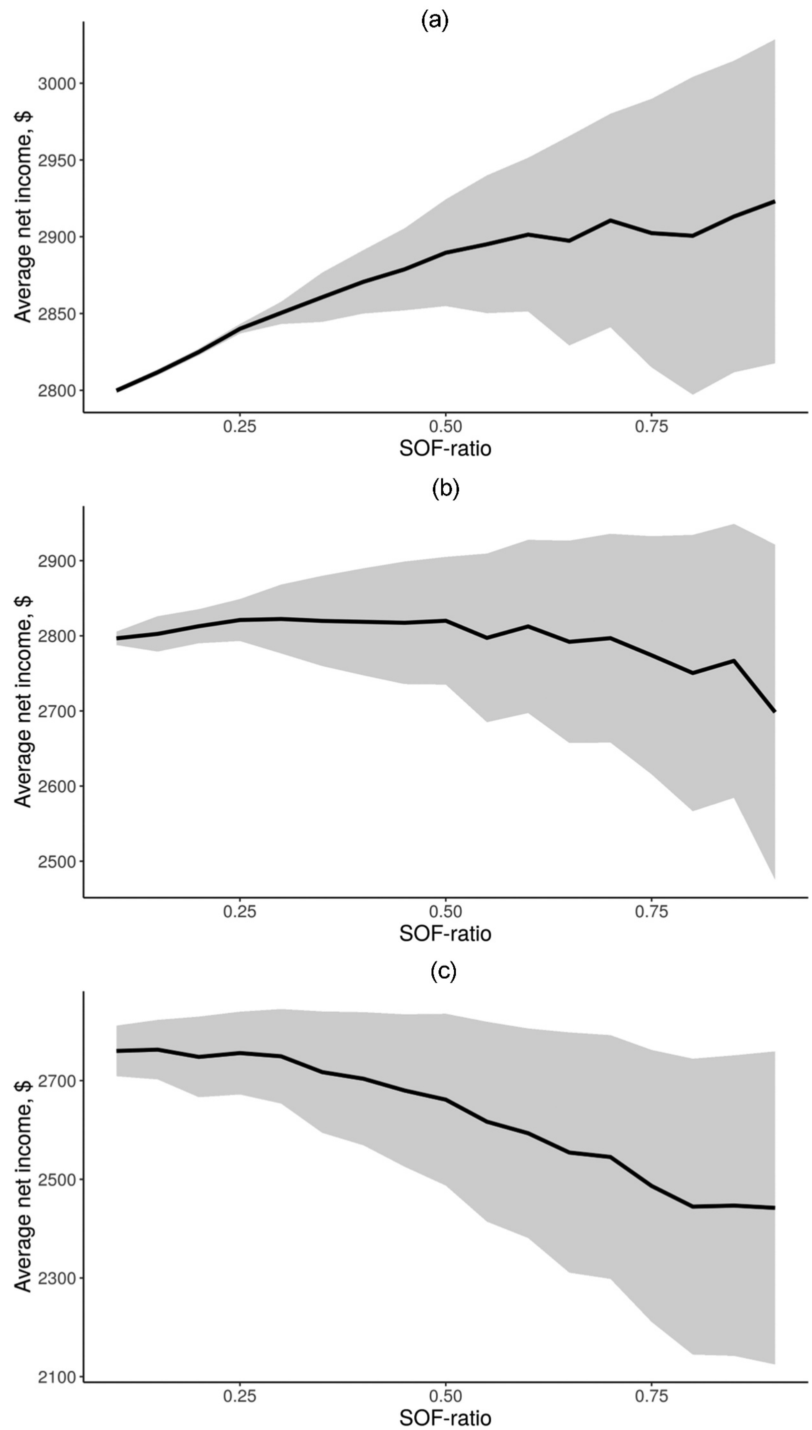

Figure 6. Average net economic gain over a period of 30 years in different communities, for the three climate scenarios: (a) current, (b) intermediate and (c) extreme climate. The shaded areas extend over the average plus and minus standard deviation for each curve. The farmers' attitude does not evolve in time (i.e. $\mu = 0$).

groundwater across the entire community. This occurs under all climate scenarios, but the effect is stronger under drier climates, when water consumption for irrigation is larger (Fig. 5).

The average net economic gain increases with SOF-ratio under the current climate, as higher SOF-ratios imply fewer on-farm ponds and hence a larger cultivated area and consequently higher yields in most years (Fig. 6(a), line). Nevertheless, higher SOF-ratios also lead to higher variability in net economic gains (Fig. 6(a), shaded area). This means that long-view-oriented farmers help the entire community towards more stable incomes. However, as seen in the previous section (Fig. 4(a)), the long-view-oriented farmers themselves are not the wealthiest. The decline of the water table depth causes increasingly frequent bad years with reduced yields. When these losses are particularly frequent because the climate is very dry (i.e. in the extreme climate) and when they are very common within the community because there is a high SOF-ratio, the entire community experiences a decline in the average net economic gain.

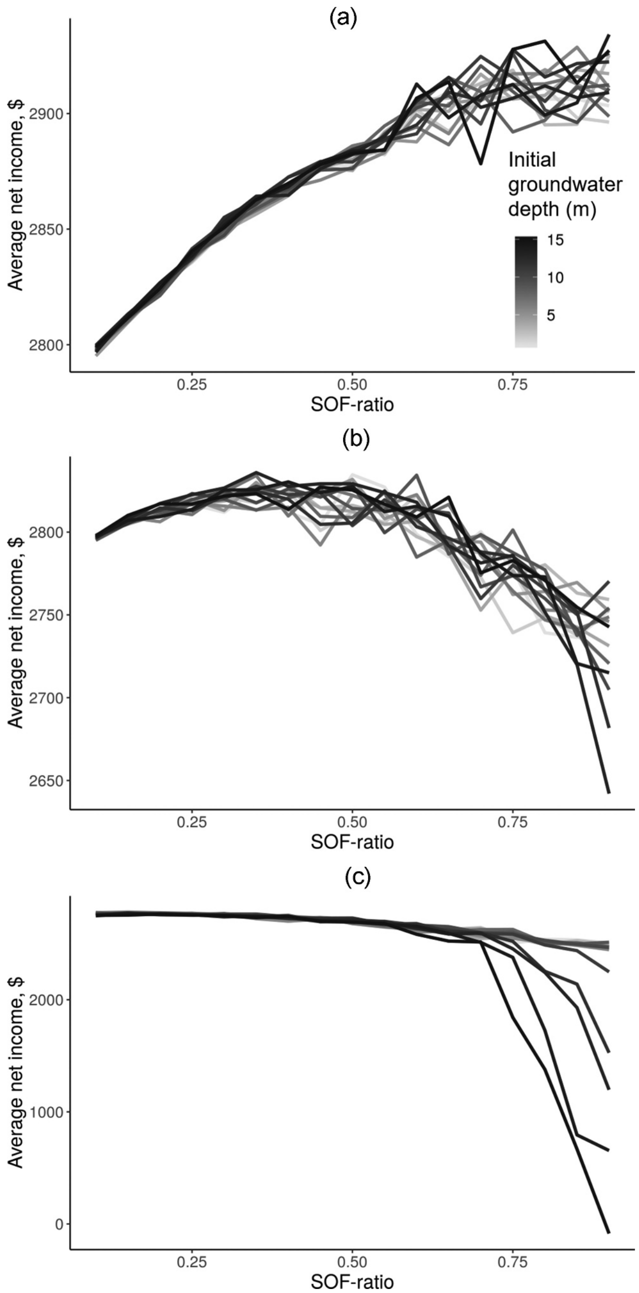

Figure 7. Average net economic gain over a period of 30 years within the different communities, for different initial depths of the groundwater (from 1 to 15 m, in steps of 1 m), for (a) current, (b) intermediate and (c) extreme climate scenario. The farmers' attitude does not evolve in time (i.e. $\mu = 0$).

Consequently, under the extreme climate scenario, communities with a high SOF-ratio are poorer, and subject to a higher variability in net economic gains, than those dominated by long-view-oriented farmers, i.e. with low SOF-ratios (Fig. 6(c)). In other words, under drier climates, the presence of long-view-oriented farmers contributes not only to more stable but also higher average net economic gains for the entire community. Furthermore, under these conditions, even single long-view-oriented farmers can be wealthier than short-view-oriented ones (Fig. 4(c)).

Figure 7 explores the role of the initial depth of the water table: this parameter affects the net economic gain of the community because the building cost of a well increases with the depth of the water table (Supplementary Material, Equation (S2)).

The same pattern discussed for the initial depth of 5 m (Fig. 6) emerges also for shallower and deeper initial water tables, with the only exception being the extreme climate scenario. In this case, for high SOF-ratios (>0.7), the initial groundwater depth becomes extremely important, leading to negative incomes for initially already deep water tables (Fig. 7(c)). The incomes, which are already reduced due to climatic conditions (cf. Fig. 7(a) and (b) with Fig. 7(c)), are not sufficient to compensate the costs for irrigation as the water table gets deeper. Under these conditions, it is very hard for farmers to get out of poverty, at least in the absence of external subsidies.

3.3 Evolution of farmers' attitudes and effects on their net economic gain

We now relax the assumption that the farmer's attitude does not change based on previous experiences and consider instead the evolution of the farmers' attitude parameters τ_i, based on the previous outcomes and the farmers' memory of them ($\mu = 0.2$; Fig. 2 and Equations (12)–(13)). Farmers who changed their behaviour (i.e. the source of irrigation water) at least once during the period considered are here referred to as "flexible" farmers. This group includes both initially short-view-oriented farmers relying only on groundwater for irrigation (with initial $\tau_i < 0.5$) who became long-view-oriented farmers (i.e. built a pond on their farm); or *vice versa*.

Figure 8 summarizes the fraction of long-view-oriented, short-view-oriented and flexible farmers after 30 years, as a function of the initial SOF-ratio of the community. Figure 9 shows the corresponding average net economic gain of the three groups of farmers.

In all the climate scenarios, the fraction of flexible farmers is small (Fig. 8). Their net economic gains are on average smaller than those of farmers not changing their orientation enough to change their irrigation strategies (i.e. farmers whose τ crosses the threshold 0.5 during the 30-year period; Fig. 9). In other words, changing irrigation strategy has negative effects on the average net income. Conversely, the income variability of flexible farmers is in between that of long-view-oriented and short-view-oriented farmers. The fraction of flexible farmers and their average net economic gain increase with increasingly dry climate scenarios.

Furthermore, under drier climates, there is a larger reduction in long-view-oriented farmers, than short-view-oriented ones. This is the case even though, under this scenario, long-view-oriented farmers who did not change their attitude would have more stable incomes and be on average wealthier than short-view-oriented ones, at least in communities with a SOF-ratio above a certain threshold (see Fig. 4(c)). Hence, the evolution of the farmers' attitude leads to a worsening of their income and its stability. This occurs because farmers' behaviour is modelled here as the one of non-rational decision-makers (Kahneman and Tversky 1979, Scholer *et al.* 2010, Kahneman 2011, Schill *et al.* 2019). Farmers thus get into what has been described as an experiential lock-in by Payo *et al.* (2016): in response to severe climate conditions, and the associated high frequency of bad years and yield reductions, they tend to become less long-view oriented (see Section 2.2.2).

4 Conclusions

Dependency on natural resources combined with ecological fragility can trigger a vicious circle, where people see their

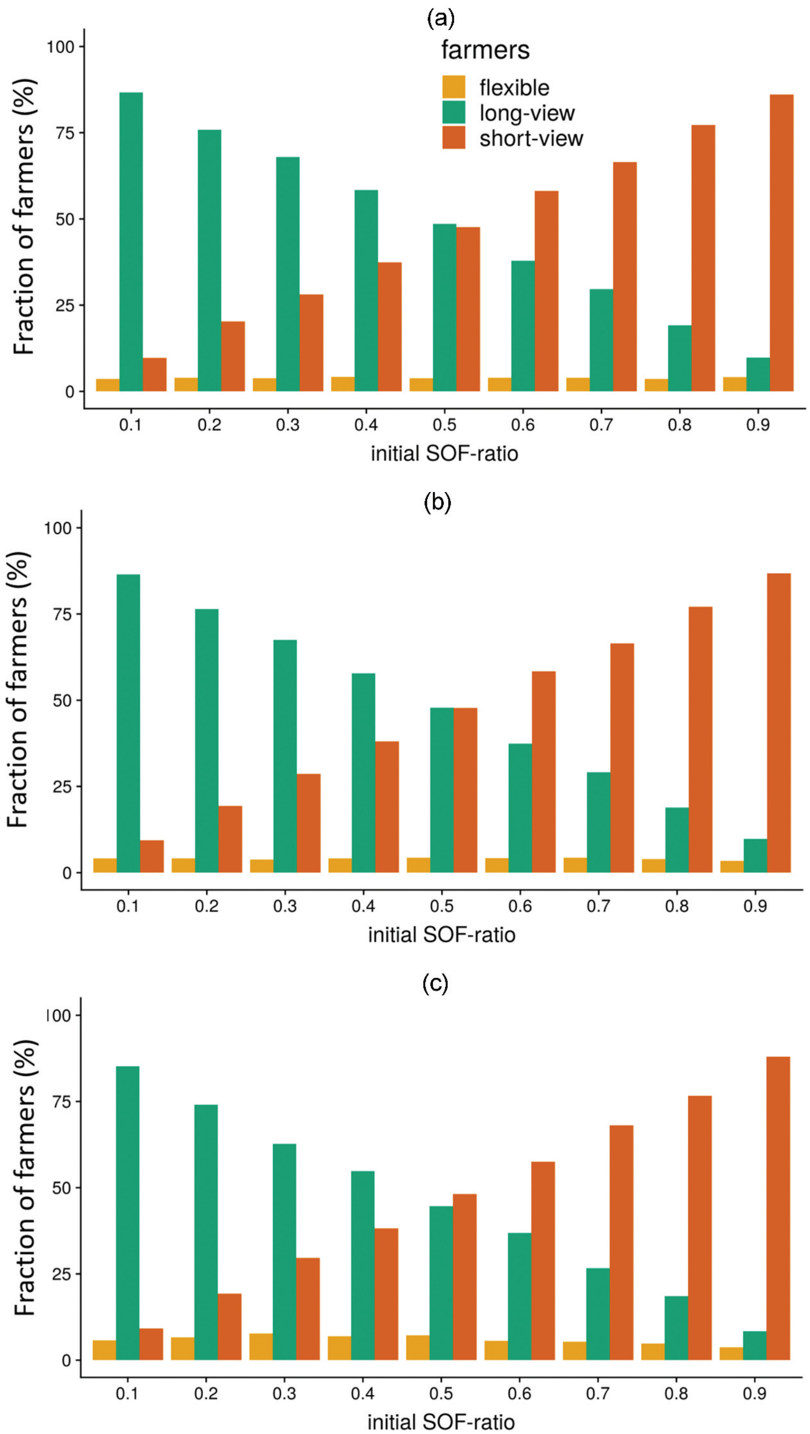

Figure 8. Proportion of long-view-oriented, short-view-oriented and flexible farmers (i.e. farmers who changed their behaviour at least once during the period considered) after 30 years, as a function of the initial SOF-ratio, under the three climate scenarios: (a) current, (b) intermediate and (c) extreme). The memory decay rate is $\mu = 2$. The values are averages over 100 simulations.

income reduced due to resource scarcity and, in order to get out of poverty, over-exploit their resource, exacerbating the situation (Cheng *et al.* 2019). Moreover, due to this poverty trap, persons cannot adopt modern technologies, which could help in improving efficiency and minimizing environmental impacts.

This risk is large in farming communities operating under potential water scarcity and using groundwater for supplemental irrigation – a common situation in many regions. On-farm ponds can help communities in avoiding such a vicious circle but require an attitude towards long-term investments and sustainable behaviours. To predict the impact of the water use behaviour on crop yields and economic gains in these contexts, we developed a socio-agricultural model where farmers, depending on their attitudes, can choose between different sources of water for irrigation (groundwater, possibly integrated with on-farm ponds). In the model, when the water table level becomes too deep to be accessible with existing wells, water for

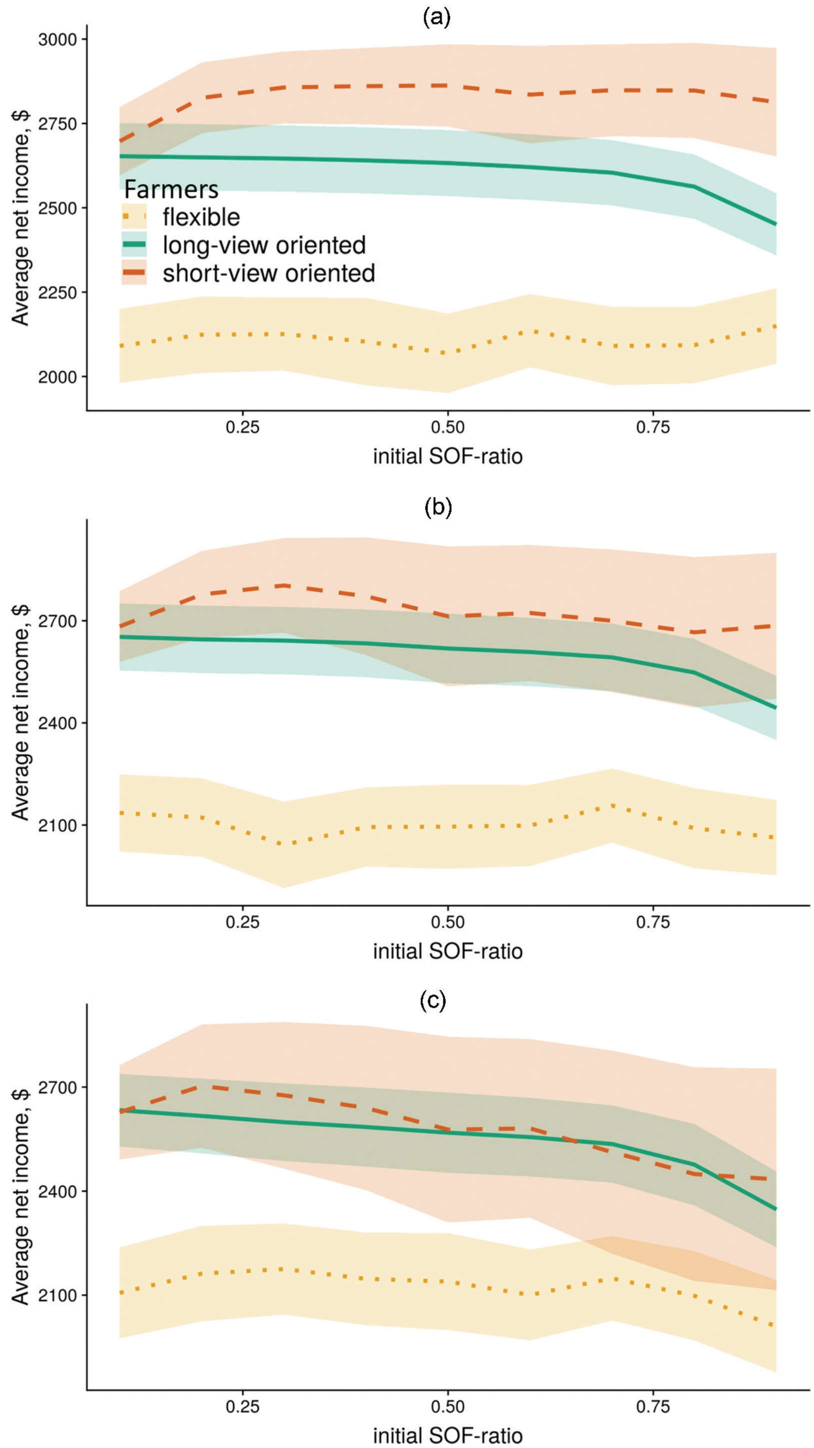

Figure 9. Average net economic gain over a period of 30 years for long-view-oriented farmers (solid green lines), short-view-oriented farmers (dashed red lines) and flexible farmers (i.e. farmers who changed their behaviour at least once; dotted yellow lines), under the three climate scenarios: (a) current, (b) intermediate and (c) extreme. Shaded areas extend over the average plus and minus the standard deviation of each curve. The memory decay rate is $\mu = 0.2$..

irrigation becomes insufficient and reductions in crop yields can occur, with negative repercussions on farm income. The frequency and entity of these losses depend on pedoclimatic and social factors, and are key factor in determining the most appropriate choice of water source for high and stable net economic gains, for both the entire community and the single farmers.

The environmental fragility-economic poverty vicious circle (Cheng *et al.* 2019) emerged in our results. Four main situations can occur and for each of them specific incentives can be devised to limit this vicious circle and enhance the application of more sustainable approaches to water management for irrigation.

(1) *Climatic conditions are severe (current climate scenario)*. In the short term, communities with high SOF-ratio are wealthier (Fig. 6(a)), because low yields are not very frequent. However, an extensive use of groundwater leads to a rapid decline of the water table (Fig. 5

(a)), with negative effects on the long-term stability of the net economic gain for the entire community and the single farmers (Figs. 6(a), 4(a) and 9(a)). Long-view -oriented farmers help the community in preventing such a rapid decline, but these farmers do not get benefits from their sustainable behaviour, except a higher stability of the crop yield (Figs. 4(a) and 9 (a)). In this situation, governments should provide incentives to build on-farm ponds.

(2) *Climatic conditions are very severe (intermediate climate scenario)*. Communities with a given percentage of long-view-oriented farmers are wealthier both in the short- and medium- to long-term (Fig. 6(b)), because long-view-oriented farmers can help in slowing down the decline of the water table and, consequently, in limiting the frequency of low yields. Again, the farmers themselves do not have benefits from being long-term-oriented, except a higher stability of the crop yield (Figs. 4(b) and 9(b)). Dynamics similar to the so-called tragedy of the commons (e.g. Hardin 1968) emerge. This is the situation where incentivizing on-farm ponds could ensure a more sustainable use of resources, as they would immediately provide advantages for the entire community.

(3) *Climatic conditions are extreme but groundwater access is still affordable (extreme climate scenario)*. Communities with a low SOF-ratio are wealthier in both short- and medium-term (Fig. 6(c)). In this case, even for single farmers, on-farm ponds are convenient, because yield losses are very frequent for all farmers, but are generally less sharp for farmers having a pond (Fig. 3). The only exceptions are communities with low SOF-ratio (Fig. 4 (c)). Therefore, incentives are theoretically not necessary. Practically, the high frequency of bad years could lead farmers to become less long-view-oriented (Fig. 8(c)), making incentive necessary, in order to avoid a more massive exploitation of the groundwater.

(4) *Climate conditions are extreme and groundwater availability is critical (extreme climatic scenario with deep water table)*. The costs of accessing water become dramatically high. This fact, combined with the reduced yields due to climatic conditions, can lead to severely reduced net economic gains (Fig. 7(c), darker lines). Breaking the environmental fragility-economic poverty vicious circle becomes hard or impossible. Priority is just survival and it may be too late for preventive actions.

These situations have been identified categorizing the farmers according to their long/short-view orientation – a crucial trait to determine their behaviour in collective action problems. Other traits can also play a role and could be considered by further extending the agent-based model, e.g. farmers' age and experience, as well as traits that depend on the spatial proximity between farmers, such as imitation and social influence.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Swedish Research Council (Vetenskapsrådet) under Grant 2016-04910; by the European Research Council (ERC) under the Consolidator Grant 771678; and by European Commission and Swedish Research Council for Sustainable Development (FORMAS), in the frame of the collaborative international consortium (iAqueduct) financed under the 2018 Joint call of the WaterWorks2017 ERA-NET Cofund grant 2018-02787.

ORCID

Lucia Tamburino http://orcid.org/0000-0003-1974-7158
Giuliano Di Baldassarre http://orcid.org/0000-0002-8180-4996
Giulia Vico http://orcid.org/0000-0002-7849-2653

References

Acheampong, D., *et al.*, 2018. Assessing the effectiveness and impact of agricultural water management interventions: the case of small reservoirs in northern Ghana. *Agricultural Water Management*, 209, 163–170. doi:10.1016/j.agwat.2018.07.009

Bouldin, J.L., *et al.*, 2004. Tailwater recovery systems for irrigation: benefit/cost analysis and water resource conservation technique in Northeast Arkansas. *Journal of the Arkansas Academy of Science*, 58 (Article 6), 23–31.

Bussmann, A., *et al.*, 2016. Sowing date determinants for Sahelian rainfed agriculture in the context of agricultural policies and water management. *Land Use Policy*, 52, 316–328. doi:10.1016/j.landusepol.2015.12.007

Campbell, G.S., 1974. A simple method for determining unsaturated conductivity from moisture retention data. *Soil Science*, 117 (6), 311–314. doi:10.1097/00010694-197406000-00001

Cavero, J., *et al.*, 2000. Simulation of Maize yield under water stress with the EPICphase and CROPWAT models. *Agronomy Journal*, 92 (4), 679–690.

Céréghino, R., *et al.*, 2014. The ecological role of ponds in a changing world. *Hydrobiologia*, 723 (1), 1–6. doi:10.1007/s10750-013-1719-y

Cheng, H., *et al.*, 2019. A circular economy system for breaking the development dilemma of 'ecological fragility–economic poverty' vicious circle: A CEEPS-SD analysis. *Journal of Cleaner Production*, 212, 381–392. doi:10.1016/j.jclepro.2018.12.014

Cialdini, R.B., Kallgren, C.A., and Reno, R.R., 1991. A focus theory of normative conduct: A theoretical refinement and reevaluation of the role of norms in human behavior. *Advances in Experimental Social Psychology*, 24, 201–234.

den Besten, N.I., Pande, S., and Savenije, H.H.G., 2016. A socio-hydrological comparative assessment explaining regional variances in suicide rate amongst farmers in Maharashtra, India. *Proceedings of the International Association of Hydrological Sciences*, 373, 115–118. doi:10.5194/piahs-373-115-2016

Di Baldassarre, G., *et al.*, 2013. Socio-hydrology: conceptualising human-flood interactions. *Hydrology and Earth System Sciences*, 17 (8), 3295–3303. doi:10.5194/hess-17-3295-2013

Di Baldassarre, G., *et al.*, 2017. Drought and flood in the Anthropocene: feedback mechanisms in reservoir operation. *Earth System Dynamics*, 8 (1), 225–233. doi:10.5194/esd-8-225-2017

El-Naqa, A., *et al.*, 2007. Groundwater deterioration of shallow groundwater aquifers due to overexploitation in Northeast Jordan. *CLEAN – Soil, Air, Water*, 35 (2), 156–166. doi:10.1002/clen.200700012

Evans, L.T. and Fischer, R.A., 1999. Yield potential: its definition, measurement, and significance. *Crop Science*, 39 (6), 1544–1551. doi:10.2135/cropsci1999.3961544x

Feng, Y., *et al.*, 2019. Comparison of maize water consumption at different scales between mulched and non-mulched croplands. *Agricultural Water Management*, 216, 315–324. doi:10.1016/j.agwat.2019.02.016

Hardin, G., 1968. The tragedy of the commons. *Science*, 162 (3859), 1243–1248.

Hay, R.K.M., 1995. Harvest index: a review of its use in plant breeding and crop physiology. *Annals of Applied Biology*, 126 (1), 197–216. doi:10.1111/j.1744-7348.1995.tb05015.x

Heggenstaller, A.H., Liebman, M., and Anex, R.P., 2009. Growth analysis of biomass production in sole-crop and double-crop corn systems. *Crop Science*, 49 (6), 2215–2224. doi:10.2135/cropsci2008.12.0709

Hofstede, G., 1991. *Cultures and organizations. Intercultural cooperation and its importance for survival. Software of the mind*. London: McGraw-Hill.

Hofstede, G., 2011. Dimensionalizing cultures: the Hofstede model in context. *Online Readings in Psychology and Culture*, 2 (1), 8. doi:10.9707/2307-0919.1014

IPCC, 2014. *Climate change 2014–impacts, adaptation and vulnerability: regional aspects*. Cambridge: Cambridge University Press.

Kahneman, D., 2011. *Thinking, fast and slow*. New York: Macmillan.

Kahneman, D. and Tversky, A., 1979. Prospect theory: an analysis of decision under risk. *Econometrica*, 47 (2), 263–291. doi:10.2307/1914185

Kuil, L., *et al*., 2018. Exploring the influence of smallholders' perceptions regarding water availability on crop choice and water allocation through socio-hydrological modeling. *Water Resources Research*, 54 (4), 2580–2604. doi:10.1002/2017WR021420

Laio, F., *et al*., 2001. Plants in water-controlled ecosystems: active role in hydrologic processes and response to water stress: II. Probabilistic soil moisture dynamics. *Advances in Water Resources*, 24 (7), 707–723. doi:10.1016/S0309-1708(01)00005-7

Moore, T.L.C. and Hunt, W.F., 2012. Ecosystem service provision by stormwater wetlands and ponds – A means for evaluation? *Water Research*, 46 (20), 6811–6823. doi:10.1016/j.watres.2011.11.026

NRAA, 2013. *Position paper 6: contingency and compensatory agricultural plans for droughts and floods in India- 2012*. DPS Marg, New Dehli: Planning Commission, Government of India.

O'Keeffe, J., *et al*., 2018. Including farmer irrigation behavior in a sociohydrological modeling framework with application in North India. *Water Resources Research*, 54 (7), 4849–4866. doi:10.1029/2018WR023038

OECD (Organization for Economic Cooperation and Development), 2013. *Providing agri-environmental public goods through collective action*. Paris: Organization for Economic Cooperation and Development, OECD Publishing.

Öhlmér, B., Olson, K., and Brehmer, B., 1998. Understanding farmers' decision making processes and improving managerial assistance. *Agricultural Economics*, 18 (3), 273–290. doi:10.1016/S0169-5150(97)00052-2

Omer, A.R., *et al*., 2019. Economic analyses of implemented tailwater recovery systems in the Lower Mississippi Alluvial Valley. *Sustainable Water Resources Management*, 5 (2), 901–919. doi:10.1007/s40899-018-0266-0

Omer, A.R. and Baker, B.H., 2019. Water quality improvements from implementation of tailwater recovery systems. *Sustainable Water Resources Management*, 5 (2), 703–713. doi:10.1007/s40899-018-0249-1

Ostrom, E., 1998. A behavioral approach to the rational choice theory of collective action: presidential address, American political science association, 1997. *American Political Science Review*, 92 (1), 1–22. doi:10.2307/2585925

Ostrom, E., *et al*., 1999. Revisiting the commons: local lessons, global challenges. *Science*, 284 (5412), 278–282. doi:10.1126/science.284.5412.278

Ouyang, Y., *et al*., 2016. Estimating the ratio of pond size to irrigated soybean land in Mississippi: a case study. *Water Supply*, 16 (6), 1639–1647. doi:10.2166/ws.2016.087

Palanisami, K., Meinzen-Dick, R., and Giordano, M., 2010. Climate change and water supplies: options for sustaining tank irrigation potential in India. *Economic and Political Weekly*, 45 (26/27), 183–190.

Pande, S. and Savenije, H.H.G., 2016. A sociohydrological model for smallholder farmers in Maharashtra, India. *Water Resources Research*, 52 (3), 1923–1947. doi:10.1002/2015WR017841

Payo, A., *et al*., 2016. Experiential lock-in: characterizing avoidable maladaptation in infrastructure systems. *Journal of Infrastructure Systems*, 22 (1), 02515001. doi:10.1061/(ASCE)IS.1943-555X.0000268

Prince Czarnecki, J.M., Omer, A.R., and Dyer, J.L., 2016. Quantifying capture and use of tailwater recovery systems. *Journal of Irrigation and Drainage Engineering*, 143 (1), 05016010. doi:10.1061/(ASCE)IR.1943-4774.0001124

Rao, C.S., *et al*., 2017. Farm ponds for climate-resilient rainfed agriculture. *Current Science*, 112 (3), 471–477. doi:10.18520/cs/v112/i03/471-477

Reba, M.L., *et al*., 2017. Aquifer depletion in the Lower Mississippi River Basin: challenges and solutions. *Journal of Contemporary Water Research & Education*, 162 (1), 128–139. doi:10.1111/j.1936-704X.2017.03264.x

Rodriguez-Iturbe, I., *et al*., 1999. Probabilistic modelling of water balance at a point: the role of climate, soil and vegetation. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 455 (1990), 3789–3805. doi:10.1098/rspa.1999.0477

Scanlon, B.R., *et al*., 2012. Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *Proceedings of the National Academy of Sciences*, 109 (24), 9320–9325. doi:10.1073/pnas.1200311109

Schill, C., *et al*., 2019. A more dynamic understanding of human behaviour for the Anthropocene. *Nature Sustainability*, 2 (12), 1075–1082. doi:10.1038/s41893-019-0419-7

Schlüter, M., *et al*., 2017. A framework for mapping and comparing behavioural theories in models of social-ecological systems. *Ecological Economics*, 131, 21–35. doi:10.1016/j.ecolecon.2016.08.008

Scholer, A.A., *et al*., 2010. When risk seeking becomes a motivational necessity. *Journal of Personality and Social Psychology*, 99 (2), 215–231. doi:10.1037/a0019715

Sikka, A.K., Islam, A., and Rao, K.V., 2018. Climate-smart land and water management for sustainable agriculture. *Irrigation and Drainage*, 67 (1), 72–81. doi:10.1002/ird.2162

Sivapalan, M., Savenije, H.H., and Blöschl, G., 2012. Socio-hydrology: A new science of people and water. *Hydrological Processes*, 26 (8), 1270–1276. doi:10.1002/hyp.8426

Song, L., Jin, J., and He, J., 2019. Effects of severe water stress on maize growth processes in the field. *Sustainability*, 11 (18), 5086. doi:10.3390/su11185086

USDA (US Departmet of Agriculture), 1982. *Ponds - planning, design, construction*. Techical report. Washington, DC: USDA Agricultural Handbook.

USDA NRCS, 2014. *Conservation practice standard irrigation reservoir*. Washington, DC: USDA NRCS.

Van den Bergh, J.C.J.M., Ferrer-i-Carbonell, A., and Munda, G., 2000. Alternative models of individual behaviour and implications for environmental policy. *Ecological Economics*, 32 (1), 43–61. doi:10.1016/S0921-8009(99)00088-9

van Valkengoed, A.M. and Steg, L., 2019. Meta-analyses of factors motivating climate change adaptation behaviour. *Nature Climate Change*, 9 (2), 158–163. doi:10.1038/s41558-018-0371-y

Vico, G. and Porporato, A., 2011. From rainfed agriculture to stress-avoidance irrigation: I. A generalized irrigation scheme with stochastic soil moisture. *Advances in Water Resources*, 34 (2), 263–271. doi:10.1016/j.advwatres.2010.11.010

Vico, G. and Porporato, A., 2013. Probabilistic description of crop development and irrigation water requirements with stochastic rainfall. *Water Resources Research*, 49 (3), 1466–1482. doi:10.1002/wrcr.20134

Vico, G., Tamburino, L., and Rigby, J.R., 2020. Designing on-farm irrigation ponds for high and stable yield for different climates and risk-coping attitudes. *Journal of Hydrology*, 584, 124634. doi:10.1016/j.jhydrol.2020.124634

Viglione, A., *et al*., 2014. Insights from socio-hydrology modelling on dealing with flood risk - roles of collective memory, risk-taking attitude and trust. *Journal of Hydrology*, 518, 71–82. doi:10.1016/j.jhydrol.2014.01.018

Wada, Y., van Beek, L.P.H., and Bierkens, M.F.P., 2012. Nonsustainable groundwater sustaining irrigation: A global assessment. *Water Resources Research*, 48 (6), W00L06. doi:10.1029/2011WR010562

Yaeger, M., *et al*., 2018. Trends in the construction of on-farm irrigation reservoirs in response to aquifer decline in eastern Arkansas: implications for conjunctive water resource management. *Agricultural Water Management*, 208, 373–383. doi:10.1016/j.agwat.2018.06.040

Zavalloni, M., Raggi, M., and Viaggi, D., 2018. Socio-ecological systems and the distributional effect of collective conditionality constraints in rural policies: A case study in Emilia-Romagna. *International Journal of the Commons*, 12 (1), 460–484. doi:10.18352/ijc.833