Supplemental Material

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

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Model parameterization
The model was parameterized for the case of the Lower Mississippi River Basin, in the southeastern USA – a region where groundwater levels have been steadily declining as the result of water withdrawal for irrigation (Reba et al. 2017b, Yaeger et al. 2018). We focus on corn (Zea mays), a commonly cultivated crop there with intermediate water use with respect to the other typical crops (soybean and cotton; Kebede et al. 2014). There is a large variation in soil textures in the region (Mostovoy and Anantharaj 2008, Livneh et al. 2015). Here we consider sandy loam soils. Climatic parameters were obtained based on standard meteorological observations in the region for the current climate scenario and then varied to simulate different climate scenarios.

The details of the model parameterization are presented below.

S1 Farm and irrigation infrastructure
Each farm in the system is assumed to have an extent $A_{farm} = 3.5$ ha, corresponding to a small-holding farming operation. On-farm ponds, when present, are idealized as rectangular parallelepiped shaped, with a depth of 2 m – as typical in the region, where ponds are constructed by moving earth and creating levees. In line with the current recommendation for on-farm pond sizing in the Lower Mississippi River Basin (USDA 1982), ponds are assumed to extend over 8% of the farm area, i.e. $A_c = 0.92A_{farm}$. This size is similar to the one leading to the highest farm production under current climate (Vico et al. 2020).

A pond of this size, when full, is able to provide about 1600 m$^3$ ha$^{-1}$ of water – approximately half of the total crop water demand during the growing season (based on the estimated ET$_{max}$ under current conditions; see below). This water capacity is in line with the guidelines by USDA NRCS (2014), which indicate a minimum water capacity of 1530 m$^3$ ha$^{-1}$ for on-farm ponds in the Mississippi area (Prince Czarnecki et al. 2016).

S2 Growing season parameters

S2.1 Soil and crop parameters
The plant available water $w_i$ is linked to the soil moisture averaged over the rooting zone as:

$$w_i = nZ_r(s - s_w) \quad (S1)$$

where $n$ is the soil porosity; $Z_r$ is the active rooting depth; $s$ is the soil saturation level ($0 \leq s \leq 1$); and $s_w$ is the soil moisture at the plant wilting point, below which the residual soil moisture becomes unavailable to the plants (and evapotranspiration becomes 0). We set $Z_r = 0.5$ m in line with global observation for crops (Jackson et al. 1996). Assuming a sandy loam, we further set the porosity $n$ at 0.43, the soil moisture level
below which the evapotranspiration begins to decline, $s^*$, at 0.46, and the soil moisture corresponding to the wilting point (i.e., the conditions at which evapotranspiration becomes zero), $s_w$, at 0.18 (Laio et al. 2001). The soil moisture above which superficial runoff and deep percolation can be assumed to occur instantaneously, $s_1$, was set to 0.80, a figure higher than the soil field capacity typical of a sandy loam to account for the fact that the hydraulic conductivity is low at field capacity, so losses at that level cannot be considered instantaneous. Using Equation (S1), we obtained $w^* = 0.06$ m and $w_1 = 0.133$ m.

The length of the main growing season (i.e., the time for corn to develop from the early vegetative stage to the first reproductive stages) is set to $t_{seas} = 70$ days, starting on 25 April, i.e., 10 days after the average planting date in the region under current conditions (USDA NASS 1997). We assumed that no supplemental irrigation is needed in the last reproductive stages.

Regarding crop development, we set $g_{max} = 0.047$ d$^{-1}$, which corresponds to the rate allowing to get a crop biomass of about 24 t ha$^{-1}$ under well-watered conditions, and hence a yield of about 13.4 t ha$^{-1}$, assuming harvest index for corn of HI = 0.56 (Pennington 2013). The HI is considered independent of the biomass production, in line with observations (Fereres and Soriano 2006). As explained in Section 2.2.1, the parameter $\beta$ (d$^{-1}$) indicates how much the biomass deteriorates in the absence of plant-available water – a situation in which carbon is lost via respiration but no photosynthesis occurs. The respiration rate is not easy to estimate, as it can vary depending on situations and species (Flexas et al. 2006). Even the ratio between growth rate and respiration rate can vary in a wide range. We chose a value in the middle of the range for this ratio, setting it to 0.2, hence we obtained $\beta = 0.2g_{max} = 0.0068$ d$^{-1}$.

Table S1. Parameters used in the growing season routines.

| Parameter | Description | Unit | Value |
|-----------|-------------|------|-------|
| $t_{seas}$ | Duration of the main growing season | d | 70 |
| $w_1$ | Soil plant available water above which losses via runoff and deep percolation occurs instantaneously | m | 0.133 |
| $w^*$ | Soil plant available water at the point of incipient stomatal closure | m | 0.06 |
| $\tilde{w}$ | Intervention plant available water | m | $w^*$ |
| $\tilde{\omega}$ | Target plant available water | m | $w^* + 0.041$ |
| $g_{max}$ | Maximum growth rate | d$^{-1}$ | 0.047 |
| $B$ | Rate at which plants deteriorate in the absence of water | d$^{-1}$ | 0.0068 |
| HI | Harvest index | - | 0.56 |
| $w(I)$ | Soil plant available water at the beginning of the main growing season | m | $w^*$ |
| $B$ | Initial plant biomass per unit cultivated area | kg m$^{-2}$ | 0.1 |

S2.2 Irrigation parameters

We assume a demand-based irrigation, where irrigation is applied when the plant available water in the soil decreases below a pre-set level $\tilde{w}$ (intervention point) and a pre-set level $\tilde{\omega}$ (target level) is restored, if there is enough available water for the irrigation application. We set the intervention point at the point of incipient stomatal closure.
closure \( \tilde{\omega} = w^* \), which corresponds to a stress-avoidance irrigation. Then we set the target level \( \tilde{\omega} = \tilde{\omega} + 0.041 \text{ m}, \) which corresponds to a furrow irrigation (Vico and Porporato 2011) – the typical irrigation technique in the Lower Mississippi River alluvial plain (Kebede et al. 2014).

**S2.3 Climatic scenarios**

The parameters more sensitive to climatic conditions are mean rainfall depth, \( \alpha \) (m), the average frequency of rainfall events, \( \lambda \) (d⁻¹), and the maximum evapotranspiration rate, \( \text{ET}_{\text{max}} \) (m d⁻¹).

For the current climatic conditions, the rainfall parameters \( \alpha \) and \( \lambda \) were estimated based on data from two meteorological stations in the Lower Mississippi River Basin area, available through the NCDC NOAA: Lambert 1 W MS, USA (34.2044N, 90.2909W, elevation 255.472 m) for the period 1942–2017, and Yazoo City 5 NNE, MS, USA (32.9027N, 90.3816W, elevation 3.26 m) for the period 1960–2017. Focusing on the growing season of corn, we determined \( \alpha \) as the average precipitation amount over the days when an event was observed; and \( \lambda \) as the inverse of the average periods between two subsequent rainfall occurrences. We obtained \( \alpha = 0.015 \text{ m} \) and \( \lambda = 0.26 \text{ d}^{-1} (\lambda^{-1} = 3.85 \text{ d}) \) for both stations. The theoretical distributions of inter-arrival times and event depth compares well with the observations (Vico et al. 2020).

The evapotranspiration rate under well-watered conditions, \( \text{ET}_{\text{max}} \), was assumed to change during the growing season as the result of seasonal changes in solar radiation and temperature. To limit the data requirements and make the climate scenario analyses possible, \( \text{ET}_{\text{max}} \) was calculated for each day of the growing season via the Priestley-Taylor formula (Priestley and Taylor 1972), assuming an empirical coefficient of 1.26. To this aim, the net absorbed radiation was determined as the difference between the shortwave absorbed and longwave emitted radiation. The shortwave absorbed radiation was calculated following Dingman (1994), assuming a reduction of 20% of the clear sky transmissivity to take into account the role of clouds, and with a crop albedo of 0.22 (Campbell and Norman 1998). The longwave radiation emitted by the canopy was determined as in Allen et al. (1998), assuming a relative humidity of 70%. The daily temperature was determined by sinusoidal fitting of daily temperature data observed over the period 1960–2017 by the meteorological station of Yazoo City 5NNE, MS, USA for the current climate. The resulting values are comparable with the pan evaporation rates measured in the same location, when a pan-evaporator coefficient of 0.75 is factored in (Vico et al. 2020) and those estimated for the same region using the Penman-Monteith equation (Yasarer et al. 2017).

Besides this climate scenario (hereafter ‘current scenario’), two further scenarios (‘intermediate’ and ‘extreme’) were considered by varying the values of these parameters. In order to simulate the expected climate change, in both scenarios the value of \( \text{ET}_{\text{max}} \) was increased, as a consequence of the projected higher temperature (IPCC 2014, Nikulin et al. 2011). Specifically, the current seasonal temperature was augmented by 2 and 4°C to calculate \( \text{ET}_{\text{max}} \) as described above for the intermediate and extreme scenarios respectively. As we were especially interested in the effects of the drought, in both cases the total precipitation amount (proportional to \( \alpha \lambda \)) was reduced, in one case by 20%, in the other one case by 50%. The precipitation distribution was also varied, simulating a regime of less frequent precipitation. To do this we doubled \( \lambda^{-1} \). The parameter \( \alpha \) was then derived from the value of \( \lambda \) and the product \( \alpha \lambda \). The three explored scenarios are summarized in Table S2.
Table S2. Climate parameters in the three climate scenarios.

| Climate scenarios               | Range of seasonal ET$\max$ (m d$^{-1}$) | Mean rainfall depth, $\alpha$ (m) | Mean inter-storm period duration, $\lambda_{\mathrm{d}}$ (d) |
|--------------------------------|----------------------------------------|----------------------------------|----------------------------------|
| Current climate                | 0.0036 - 0.0048                        | 0.015                            | 3.85                             |
| Intermediate climate (-20% precipitation; +2 °C temperature) | 0.0038 - 0.0050 | 0.019                            | 6.09                             |
| Extreme climate (-50% precipitation; +4 °C temperature) | 0.0040 - 0.0052 | 0.015                            | 7.70                             |

S3 Non-growing season parameters

S3.1 Economic parameters

We were not interested in the precise income of the farmers, but in the proportion between the different budget lines and their initial capital, to see how the income evolves over time. On-farm pond and well costs are the crucial budget lines in our model.

Pond construction costs can vary enormously. We recall that our model simulates a small-holding farming system, with simple ponds of a small/medium size, each of them serving a single farm. A similar system was described in Mushtaq et al. (2007). There the cost for pond construction and maintenance was indicated to be around US$2000–3000. Taking into account the current prices in the US-market for irrigation ponds, we set the cost to US$4,000.

Even the costs of a groundwater extraction system (well and pump combined) can vary hugely depending on several factors, such as geologic conditions, depth and kind of pumping system. Geological conditions are not included in our model, as they are assumed to be identical for all the farms. The depths explored in our model vary in the range between 1 and 20 m, in line with the groundwater depth in the Lower Mississippi River Basin (mainly between 0.4 and 25 m, even though in the most critical areas of Arkansas it can reach up to 30–35 m and, and in the most extreme case 40 m; Reba et al. 2017a). In Dumler et al. (2007) the costs for well and pump combined together are suggested to be around US$50 000, when referring to wells with a depth of 300 ft (91.5 m). Although costs are not perfectly linear, this suggests a cost around US$2700 for a 5 m deep well, confirming that a well is generally cheaper than a pond, but that the cost increases with the depth and can become more expensive. The kind of groundwater extraction system depends on the depth, with a shift in the most suitable technology from spearpoint between 5 and 10 m and shallow bore from 10 to 30 m (Robinson 2002). Note that 10 m is close to the theoretical depth (10.3 m) at which the pressure of the air sucking the liquid equates the atmospheric pressure and cavitation risk arises. Based on these considerations, we set the well costs as linearly increasing with the depth until the threshold 10.3 m. At this threshold the cost equates the pond cost, then it increases again with the depth, but with a higher coefficient, due to the different and more expensive technology required. The formula is:

$$
c_w = \begin{cases} 
d_{w,i} \cdot \frac{c_p}{10.3} & \text{if } d_w \leq 10.3 \text{ m} \\
d_{w,i} \cdot c_d & \text{otherwise} 
\end{cases} \tag{S2}
$$

where $c_w$ is the cost of a well (well and pump combined), $c_p$ the cost of building a pond, $d_{w,i}$ indicates the well depth in meters, and $c_d$ is the linear cost of the well above the
threshold, with $c_d > (c_w/10.3)$. In the simulations, we set $c_d = 2(c_w/10.3)$, consistently with the cost difference between spearpoints and shallow bores.

The farmers’ initial capital is set to twice the cost of the pond, in such a way that, if the water table is less deep than the threshold of 10.3 m, each farmer has money enough to build both pond and well from the beginning. For the pond, we assumed a lifespan of 25 years (Omer et al. 2018, Rao et al. 2017, Mushtaq et al. 2007). Well pumps do not have a precise lifespan, but a probability of breaking that increases linearly with the age, with an average expected lifetime of a pump is 15 years (Hogan et al. 2007). To simulate this, in the model the pump age is multiplied by a random number extracted from a uniform distribution in the interval [0,1) and then divided by 7.5. The result is compared with 1: if greater, the pump is considered broken and in need of replacement.

The income from the yield in a given year depends on the crop price $c_Y$ (US$/kg), and the attained marketable yield $Y(t) – a$ function of the the crop biomass at the end of the main growing season, $b(t)_{\text{tongas}}$. We set $c_Y = 0.17$ US$/kg$, according to the corn prices during the last years.

The expenses $O_i(t)$ are determined as the sum of fixed costs, independent of the cultivated area; and costs linearly increasing with the cultivated area. Hence,

$$O_i(t) = c_f,f + c_f,w A_{c,i}(t) \quad (S3)$$

The dependence on time is given by the possible change in cultivated area, because of the building or removal of the on-farm pond. The parameters were estimated as $c_f,f = 400$ US$ and $c_f,w = 0.2$ US$ m^{-2}$, based on Mushtaq et al. (2007).

3.2 Attitudinal parameters

The attitude parameter of the $i$th farmer $\tau_i$ varies depending on the memory $M_i$, which in turn depends on the memory decay $\mu$. We assumed the same $\mu$ for all the farmers, and performed a sensitivity analysis varying it in the range 0 to 0.2, similarly to Viglione et al. (2014). We observed that $\mu$ affects only the percentage of ‘flexible’ farmers: the percentage increases with the value of $\mu$. Therefore, we showed results for the two extreme cases: $\mu = 0$ (Sections 3.1–3.2 in the main text) and $\mu = 0.2$ (Section 3.3 in the main text).

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