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LETTER

HELGA: a global hydro-economic model of groundwater-fed irrigation from a farmer's perspective

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Abstract

Overexploitation of groundwater for irrigation can ultimately threaten the viability of agriculture itself, because the falling groundwater levels become too deep to sustain the increasing costs of groundwater extraction, an economic limit is reached. In order to evaluate possible adaptation strategies to avoid or postpone reaching the economic limit, we developed the microeconomic heuristic model HELGA (hydro-economic limits as a global analysis). HELGA considers the interaction of groundwater with irrigation at the farm level with a global scale application in mind. HELGA evaluates the development of the costs and revenue of groundwater-fed irrigated agriculture from the farmer's perspective. As long as the farm remains economically viable, the farmer can invest to access deeper groundwater, but in the long run the famer may have to adapt to keep farming profitable. We applied HELGA in five locations within the conterminous USA. In most cases, recharge is large enough to save a farmer from reaching the economic limit. Where groundwater is overexploited, the increasing energy cost of groundwater pumping is one of the main drivers limiting groundwater use. Additionally, the increasing costs of the water infrastructure (i.e. deeper wells) is a crucial factor that explains where and when the economic limit is reached. If farmers change crops wisely or fallow part of their land, they are able to access groundwater longer and postpone the moment the economic limit is reached. Using HELGA, we show that proper and timely adaptation measures increases the profitable lifetime of groundwater and helps to conserve this resource for future generations.

1. Introduction

Irrigation is needed to sustain agriculture when the availability of soil moisture is limiting (Grafton *et al* 2018, CBS Statistics Netherlands 2020). Irrigation water is commonly taken from groundwater and surface water. While surface water often is a more accessible resource than groundwater, groundwater naturally buffers climate variations (Schoengold and Zilberman 2004, Rahmah *et al* 2012, Dhawan 2017) and it is less prone to pollution (Awoyemi *et al* 2014).

Groundwater thus provides a reliable source for irrigated agriculture but when withdrawals exceed the available recharge for a long time, the groundwater resource is depleted and groundwaters drop persistently (Schoengold and Zilberman 2004, Siebert *et al* 2010, Bierkens and Wada 2019). This problem may deepen in the future as climate change may have a negative effect on the recharge of aquifers (Dragoni and Sukhija 2008, Green *et al* 2011, Amanambu *et al* 2020, Berghuijs *et al* 2024). The consequence is that farmers must extract groundwater from increasingly deeper wells and incur greater costs for well construction and for the energy required to lift the water to the surface (Bierkens *et al* 2024).

Investment costs and the perceived unlimited supply of groundwater may contribute to the adoption of groundwater as the primary source of irrigation water. Groundwater is also used by other sectors (Foster *et al* 2011, Müller Schmied *et al* 2021) and often preferred because of its good quality (e.g. for drinking water). This increases the competition between groundwater-fed irrigation and other sectors; the associated background pumping rates may lead to a faster decline of the groundwater levels, subjecting farmers to greater costs.

Where groundwater-fed irrigation is a necessity for profitable agriculture, farmers may be confronted by the fact that the rising costs of groundwater extraction eventually exceed the revenues. When this happens, the economic limit is reached. Bierkens and Wada (2019) postulated that the economic limit could be reached before the groundwater becomes physically exhausted, but they did not quantify it. Together with the environmental limit (de Graaf *et al* 2019) these limits define the safe operating space in which groundwater-fed irrigated agriculture can be profitable and sustainable in the long run.

When confronted with the higher costs of accessing scarcer groundwater resources, the farmer will adapt to stay in business. Actions and decisions by the farmer at the (local) farm level, may impact larger scales, especially when done collectively. Evidently these impacts concern the hydrological system but they may also extend to global markets as farmers react to changes in costs and prices on the one hand, while the changes in production -due to variations in yield or cropped area- influence market prices on the other.

Starting from the problem of groundwater fed irrigation, we developed a microeconomic heuristic model called HELGA (hydro-economic limits as a global analysis). HELGA is a modelling tool that is intended to be applied at the global scale to explore potential adaptation pathways to secure longer access to groundwater for irrigation by farmers and to avoid the physical and economic impacts of overexploitation. Thus, it aims to support sustainable and profitable food production and contribute to minimize conflicts over resources within the Water-Energy-Food-Ecosystem nexus. HELGA combines three components of food production (hydrology, economy and agriculture) and evaluates their interactions at farm level. Farmers are given some generic agency to make investments in order to maintain access to groundwater resources and to adapt to keep the farm profitable and to avoid reaching the economic limit, for example by making irrigated agriculture more water efficient or more profitable. In this study, HELGA is applied stand-alone, and it is fed one-way with hydrologic and economic information to introduce the model concepts in detail. We envisage HELGA as an integrated part of a model structure in which information at farm level is exchanged with other models, to fully capture the dynamics and to evaluate whether farming is sustainable in the long-term from an economic and environmental perspective, and what adaptation strategies or policy instruments are necessary to achieve this.

HELGA follows a bottom-up approach and operates at a different intended scale than existing hydro-economic models. The model works under a simple decision making (instead of a complex optimization or a random behaviour in the farmers decision making or the aquifer MacEwan *et al* 2017, Ward *et al* 2019, Afshar *et al* 2020, Rouhi Rad *et al* 2020, Rodríguez-Flores *et al* 2022) and integrates hydrology, agriculture and economy from a local farmer's perspective (Escriva-Bou *et al* 2017, Gohari *et al* 2017, Huang *et al* 2018) in a modular fashion (MacEwan *et al* 2017). Moreover, HELGA propose a stronger linkage between the financial cost/burden of water investment with the crop change mix adaptation strategy, unseen in other hydro-economic models (Rouhi Rad *et al* 2020).

This paper describes the overall model concept of HELGA, its structure and data requirements. Next, HELGA is applied to five locations with groundwater irrigation in the conterminous USA to portray how a farmer's investment perspective changes and he adapts in response to climate variability and the falling groundwater levels in the case of overexploitation. We conclude by considering HELGA in relation to the existing theory of hydro-economics and by providing an outlook on future developments and applications of HELGA in a global water resources context.

2. HELGA

2.1. Rationale

In HELGA, agricultural production from crop cultivation is evaluated at the farm level. Here, we define a farm as a business with access to land and water resources with the primary objective of cultivating, harvesting and marketing crop produce for revenue. At the farm level, decisions are made by the farmer (figure 1); we indicate this farmer by *he/him/his* but do not imply that this is a single male person but rather a figurehead encompassing all persons involved in farm management.

HELGA places the economic behaviour and decisions by the farmer on crop cultivation at the centre. HELGA considers primary production, i.e. the harvested product that is being sold at the gate. Presently, it assumes a 1:1 relationship between crop grown and the product harvested. Crops can be both annual and perennial crops. Crop cultivation incurs costs and including those for labour and (indirect) wages of the farmer and his family.

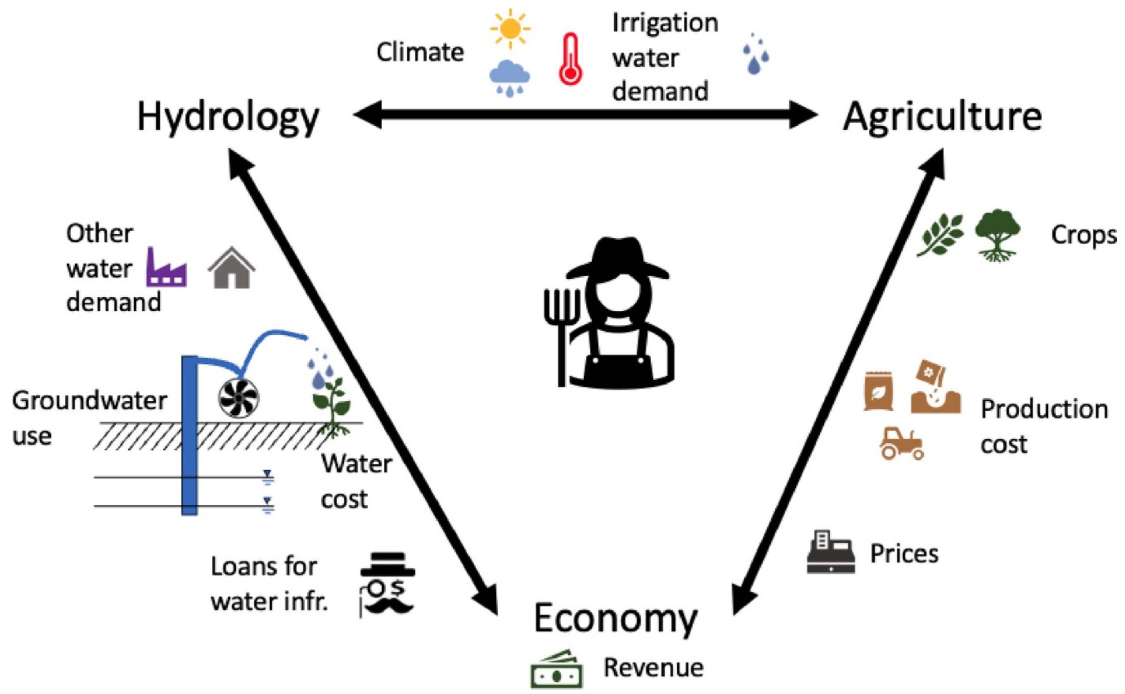

Figure 1. HELGA structure with the three main components: hydrology, agriculture and economy. Where climate, initial crop mix, prices, and other sectors water demand are exogenous variables. Irrigation water demand, production cost loans for water infrastructure, groundwater use and water cost are endogenous.

In HELGA, farmers continue farming as long it is economically viable, and they will adapt the farming operations at different moments and in different manners to maintain profitability (see below). We define a farm to be economically viable if the farm can secure access to sufficient water to produce crops profitably; to remain in business the farmer should accrue a minimum buffer to survive incidental losses. Farmers actively make decisions that are conditioned by external factors (figure 1). Each of these factors influences the behaviour and the decisions by the farmer as will be described in detail below: in case of agriculture, the crops and production methods open to the farmer constrain his operations; in case of hydrology, the production and costs may vary as a result of climatic variability or because of falling groundwater levels that can only be accessed at greater costs; and in case of the economy, investments may be more expensive depending on the interest rate when farmers have to borrow money and the revenue may vary with market prices. Changes at farm level may propagate to the regional and global scale. For instance, farmers can compete among each other and with other sectors for access to groundwater, and changes in the crops grown may affect crop prices in turn.

The number of interactions can be large and depend on the nature of the coupling of HELGA with other models tailored to model regional to global developments for each group, for example a large-scale hydrological model, a crop production model or a macroeconomic model. HELGA evaluates the economic dynamics of a farm on an annual basis and per calendar year, shorter term dynamics can be implicitly considered by means of the coupling, with a proper aggregation. Nevertheless, the version of HELGA presented in this paper uses a simplified version of a groundwater and agricultural models. To facilitate coupling, HELGA is set up in a modular fashion in which the relevant outputs from other models can be ingested and the output from HELGA can be passed back to inform other models. HELGA is coded in python and is object-based. We refer to some objects here to clarify where information on parameters and state variables are stored in the model.

2.2. Farms in HELGA

In HELGA, the revenue and costs reflect the farm operations at the field level (described in detail in the supplementary material). Every farm consists of several fields that constitute the agricultural area of that farm and the assets that are needed for the production. In this study, only farms with fields equipped for groundwater irrigation are considered. However, HELGA provides flexibility as each field is represented as an object with a number of physical and economic attributes (described in detail in the supplementary material). They comprise among others the area of the field and which crop is cultivated. The *actual*, real annual values at the field level determine the actual yield, the production and revenue, and they reflect the production costs. In this stand-alone version of

HELGA, we simulate the crop water requirements, the irrigation water demand, withdrawals, and the yield directly for the current cropping season for which the harvest date falls in the current calendar year, but our intention is to retrieve this information from hydrological models and/or crop growth models that better represent the actual processes involved. The actual values are aggregated to long-term values using an N-year running mean that provide the basis for decision-making (see next section).

Crop information is required at different stages in the model structure and is stored in a designated object per crop type, that keeps track on current and past crop properties, status and performance. Essentially, this includes actual crop information that has to be shared across fields such as the update, but also the producer price and the parameters defining the non-water related production costs (other costs). In addition, the crop object provides long-term estimates on aspects of the costs related to crop production per cultivation type that is aggregated from the field objects of the farm. Thus, the crop objects provide essential information that the farmer needs to make decisions on what crops to grow and how this informs his decision-making.

Actual long-term performance is still kept at the field level, but this would be reset and initialized from the crop object in the case of crop rotation at farm level. Furthermore, long-term information from the crop objects can be shared among farmers, for example with neighbours, in a region etc, thus giving farmers new opportunities to expand their investments and increase the profitability of their farm.

2.3. Adaptation and decision-making in HELGA

A farmer constantly makes choices that directly or indirectly affect the profitability of his farm. As the farmer is aware of his environment, he will strive to detect problems, define the problem, make decisions and implement the solution (Öhlmér 1998). Profitability is maintained as long as the gross revenue of cropping exceeds all the costs and the change in the savings is larger than or equal to zero. In this application of HELGA, a farmer has to make decisions on what crops to cultivate and how to secure sufficient irrigation water. The decisions by the farmer always reflect the changing economical and hydrological conditions to which he is subject and to which he has to adapt. Whether this is possible or not, depends on the agricultural technology at his disposal (figure 1). The basic assumptions are that a farmer will continue farming as long as he expects this activity to be profitable and that irrigated agriculture ensures a higher and more reliable yield.

When making an investment, the future profitability over the lifetime of the asset is assessed by the net present value (NPV), that gives the return on the investment:

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{R_{\mathrm{Gross}\,t} - OC_t - \sum_w^W C_{\mathrm{I}wt} - \sum_w^W C_{\mathrm{V}wt}}{(1+d/100)^{t-1}}. \tag{1}$$

Here, t denotes the time in years over the projected lifetime of the investment T, R_{Gross} is the gross revenue, OC are the other costs, C_{I}[4] and C_{V} the investment cost and variable cost for the water source, w, all in USD, and d[5] $[-]$ is the discount rate (%; set by the market). Note that the projected revenue and costs may vary dependent on the farmer's perception are therefore variable in time.

How the farmer looks at this NPV for the investment period depends on his position. When the farmer needs to secure a loan from the bank to make this investment (figure 2), then the NPV should be equal to or larger than zero. If the farmer pays for his investment out-of-pocket, he may consider a negative NPV dependent on the liquidity of the farm, if he believes this would take him through a particularly rough patch, and this is defined by:

$$\mathrm{NPV} + S\sum_{t=1}^{T} \frac{(1+i_{\mathrm{s}}/100)^{t-1}}{(1+d/100)^{t-1}} \geqslant 0. \tag{2}$$

Note that the savings consider the interest rate i_{s} [%] in relation to the discount rate. As the length of the investment period is considered, this evaluation in terms of savings is more positive for shorter-term investments as both the investments are probably smaller and the countervalue of the depreciating savings higher.

In HELGA, a farmer makes his decisions from a perspective of bounded rationality (Öhlmér 1998, Simon 2000); the information underlying his decisions is based on past performance for his own farm or that from fellow farmers in his vicinity. As such, decisions are always sub-optimal. Furthermore, the farmer will change operations to turn around recurring losses or to increase his gains and update the infrastructure to ensure his farm is viable in the long-term. Decisions related to these aspects can be subdivided broadly into two categories, the former being *reactive* and the latter being *proactive* (figure 2).

Over the years, the farmer reacts to poor revenue in the past and will decide which crops to plant. Farmers will tend to eliminate crops that have not been profitable repeatedly and may opt for more profitable crops than the ones currently present on his farm.

When the remaining lifetime of an asset is insufficient to cover the coming operational year, the asset

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[4] The cost of the infrastructure is defined as the sum of the values of the pump, well and irrigation infrastructure: $C_{\mathrm{I}} = V_{\mathrm{well}} + V_{\mathrm{pump}} + V_{\mathrm{infra}}$.

[5] In this case, the discount rate expresses the opportunity cost of investing in other assets.

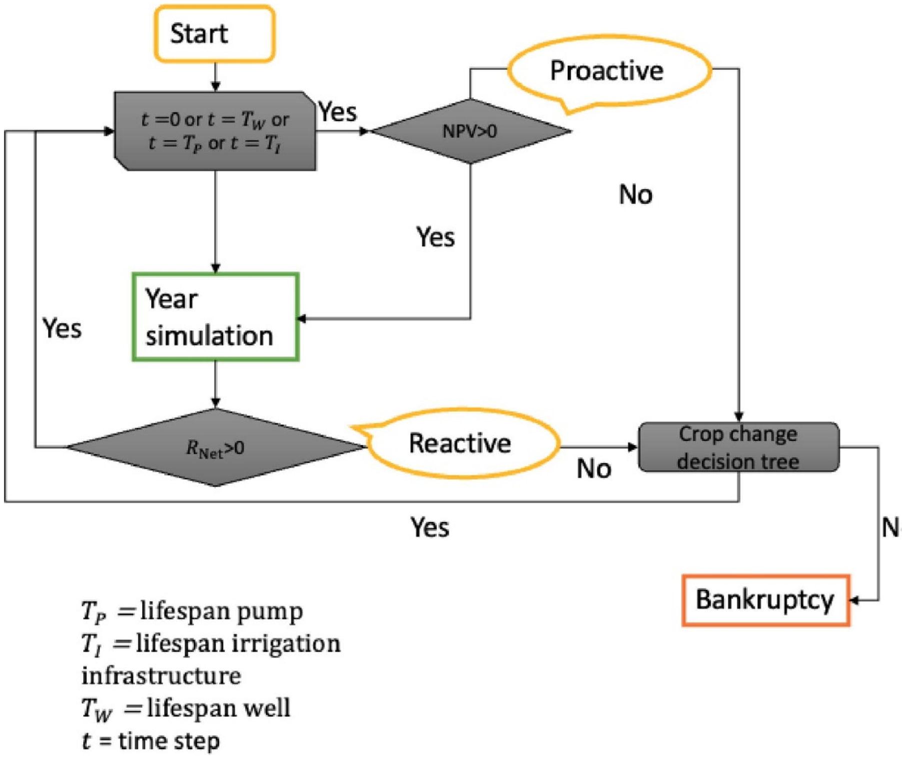

Figure 2. Flow chart of farmer's decisions in HELGA. Depicting the decision making yearly and the exceptions made when the NPV from the groundwater infrastructure requires replacement or crops decline in their net revenue. Currently, inflation is not considered in HELGA, prices are fixed, but it can be incorporated by correcting the relevant long-term values prior to the update for the actual year.

has to be updated. In making this investment, the farmer proactively looks ahead over the expected lifetime of the asset and designs it according to the projected revenues and costs based on projected yields and projected groundwater level change. If the projected investment is not economically viable for the current crop mix, alternative crop mixes can be considered as part of the process. The crop mix change process involves the steps described in detail in the supplementary material.

In the case of the crop selection, expected values of the costs and producer prices can be estimated using the mean and the past trend. How farmers perceive the development of the costs and prices in the short and long run is one way to attribute traits to farmers in HELGA and modify their behaviour.

In HELGA, decisions are made at the end of the update of the current year. Thus, the model can ingest information from external models in the coupled framework (e.g. groundwater tables, irrigation water demand and supply, yield and producer prices), process it, and pass information on the new crop mix and assets to the coupled models (e.g. crop area, cultivation types, well depths etc). A particular case arises at the start of HELGA, when the farmer has to make a selection on the crop, on the cultivation type, on the provenance of water for irrigated areas, and on the assets needed to secure his irrigation water supply. Crop areas, cultivation types and irrigation techniques are currently set on the basis of external databases (see below) but could also be evaluated as part of the spin-up procedure (see the SI). As the actual income of the farmer may be lower than expected due to adverse climatic conditions at the start of the simulation and he may not have yet accrued enough savings, he is given until the first proper investment decision -when he in theory has to go back to the bank for a new loan- to prove the profitability of his farm.

2.4. Model parameterization and application

The intended scale of application of HELGA is global, and we prefer to derive HELGA's inputs and parameters from openly available global data sources. Information on physical properties, such as groundwater hydrology and meteorological forcing and the agricultural conditions including irrigation types per crop is mostly available as gridded information. In this case, we take these from the inputs, parameters and outputs of PCR-GLOBWB 2 (Sutanudjaja *et al* 2018), which has a spatial resolution of 5 arc minutes (∼10 km at the Equator). Economic parameters and inputs such as the discount rate, interest rates, producer prices and costs are mostly available

Table 1. Overview of the data used in this study and their sources (see Bierkens *et al* 2024 for details).

Database	Type	Source
Crop Mix: MIRCA 5 arc minute	Global map with the crop coverage in a 5 arc min resolution	Portmann *et al* (2010)
Water productivity	Country level data	Mialyk *et al* (2024)
Irrigation type	Country level data	Jägermeyr *et al* (2015)
Irrigation cost	Country level data	Hogan *et al* (2007)
Energy cost	Country level data	Asafu-Adjaye (2000), Eurostat (2021), Ghosh (2002), Lise and Van Montfort (2007), OECD (2020)
Production prices	Country level data	Food and Agriculture Organization of the United Nations (FAO) (2021)
Interest rate	Country level data	World Bank (2020)

from statistical databases at country level[6] (Food and Agriculture Organization of the United Nations (FAO) 2021). Economic information in a subnational or regional level is challenging to find, the current version of the model uses available and curated information. For subnational or regional analysis, HELGA has the flexibility to use local data instead of country level information. A detailed overview of the data and their preparation can be found in Bierkens *et al* (2024) a brief overview is presented in table 1.

To demonstrate its functionality, HELGA has been applied for five selected farms in the Contiguous United States of America (CONUS; see figure 3), which covers a wide range of crops and climate conditions. While this study does not attempt to validate the model, CONUS is a relatively data-rich region and an obvious region for validation at later stages. Here, we take each farm to be equivalent with a single cell of 5 arc minutes of MIRCA (table 1), from which we derive the crop composition. Consequently, the size of a true farm at these locations may be overestimated in this study, and this may exaggerate the economy of scale in supplying the farm with irrigation water. However, we believe this approximation does not prevent us from demonstrating the functionality of HELGA. Due to the high cost involved in the implementation and use of groundwater the algorithm design only keep crops able to sustain the cost of withdrawing groundwater, this assumption may underestimate the groundwater demand given that we are not considering subsidies.

The farm size compared to other hydro-economic models is bigger by at least for two orders of magnitude (MacEwan *et al* 2017, Afshar *et al* 2020, Rouhi Rad *et al* 2020, Rodríguez-Flores *et al* 2022), which would be seen as a limitation. Nevertheless, HELGA design as a farm composed by fields provides the versatility to being used in a smaller resolution, if necessary and if there is data available at the desired scale. This scale paves the way for the further global application.

To illustrate the functionality of HELGA, four scenarios have been, covering the period from 2000 to 2100. Scenarios 1 through 3 emphasize the farmers' possibilities to maintain the profitability of their farms. Scenario 0 enforces groundwater depletion across all locations by assuming zero recharge. This scenario serves as a case in which the economical limit of groundwater-fed irrigation will be more easily met. In the scenarios allowing crop change (Scenarios 2 and 3), areas with unprofitable crops will transition to more profitable crops under groundwater-fed irrigation or eventually become fallow.

Our simulations consider groundwater-fed irrigation only that has to meet any crop water requirements that were not satisfied by the available soil moisture. We coupled HELGA one-way to PCR-GLOBWB to obtain the necessary hydrological input, using timeseries of 40 annual values that were repeated over the duration of the simulation. Input includes groundwater recharge as well as the crop water requirements and soil moisture availability over the irrigated areas. The current coupling to PCR-GLOBWB does not feedback into the hydrology of PCR-GLOBWB; rather, the groundwater hydrology was simulated directly by HELGA at farm level and its dynamics arise directly as a result of the irrigation water practices simulated at farm level. When fully coupled, HELGA will be coupled to the version

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[6] In the case country information is lacking, a default value is substituted that is based on the mean value from the available countries within the same of 26 economic regions from the integrated assessment model IMAGE (PBL 2022).

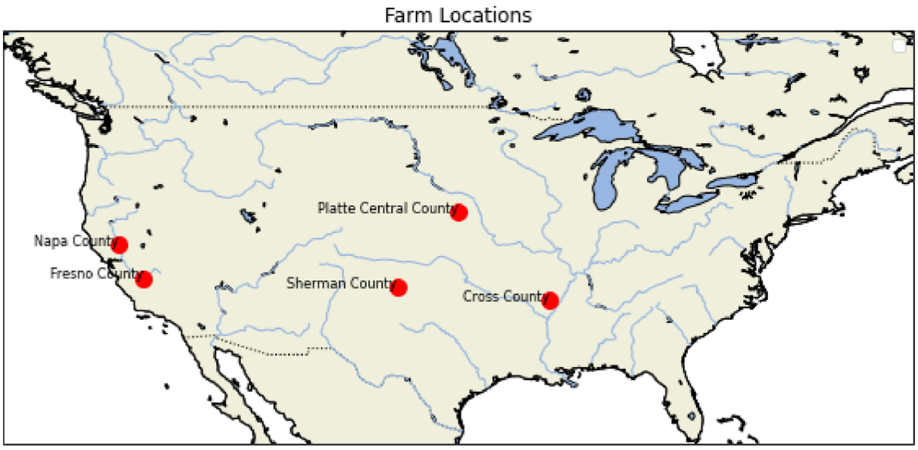

Figure 3. Location of the farm locations within CONUS evaluated with HELGA in this study. Farms were selected on the basis of a high groundwater demand and crop mixes that reflect varying climatic and soil conditions: Fresno County and Napa County (CA), have the largest range in crops, including cash crops. Platte Central County (NE) and Sherman County (TX) are located on the Ogallala Aquifer and Cross County (AR) on the Mississippi Embayment. The last three farms primarily cultivate staple crops. The amount of groundwater recharge and the hydrogeological conditions varies across all five farms (see for farm details the supplementary material).

of PCR-GLOBWB in which the groundwater is simulated with MODFLOW, in order to also simulate the lateral exchange of groundwater across the aquifer, which may influence groundwater dynamics at farm level.

We use the scenarios to evaluate model behaviour and sensitivity in terms of the changing groundwater depth, costs and revenues, and savings by evaluating short-term variations and long-term trends under consideration of the changes in crop types and irrigation technology as part of the adaptation strategies. The crop type other perennials of the MIRCA dataset is somewhat hard to incorporate as the actual crop grown is not provided but it concerns cash crops contributing disproportionally to the revenue. We therefore do the analysis here without any perennial crops but include them in an additional analysis in the SI.

3. Results

The significance of recharge on the emerging groundwater depths cannot be overstated. The most important impact of incorporating recharge in the model concerns the electricity costs[7], which constitute a larger percentage in the ‘Race to the Bottom’ scenario, particularly for Platte Central. At Sherman, staple crops dominate the crop mix and this farm is unprofitable in this scenario; only when recharge is included the farm becomes profitable (figure 4). The importance of cash crops is evident from the analysis that includes the perennial crops in the supplementary material. The interplay between recharge rate and electricity costs is noteworthy. With recharge, wells do not reach the projected depth and their lifetime exceeds the standard lifespan. This has significant financial implications, effectively reducing the investment costs related to wells and pumps, as a smaller capacity suffices for the latter.

The Proactive and Proactive + Reactive scenario permit changes in the crop types and in irrigation techniques as part of the adaptation strategy (table 2). Allowing such changes makes groundwater-fed irrigation more profitable and sustainable, as is the case for Fresno, Cross and Napa (figure 4); Platte Central and Sherman remain profitable and show respectively a decreasing dependency on loans and an increase in profitability. Such an increase in profitability can also be observed for Fresno if yearly updates in the crop types is permitted: unprofitable crops are discontinued and exchanged for other, more profitable crops or left fallow (figure 5). The case of Fresno highlights the general tendency in figure 5. Crops such as cotton and potatoes contribute substantially to the overall profit, compensating for less profitable crops like sorghum. For Fresno this leads to increased profitability. This effect is not always positive. For Cross, more profitable crops allow non-profitable crops to be sustained in the Proactive scenario, as the NPV is evaluated positively throughout (equations (1) and (2)). However, annual updates exclude more crops while initial investments are high and as a consequence the economic limit is reached. This underlines the effect of climate variability as during unfavourable years, even the profitable crops struggle to sustain long-term profitability, resulting in a significant impact on the farm’s total profits.

The proactive and reactive scenarios show that making decisions based on (past) short-term negative results can be counterproductive, as it may involve

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[7] It was assumed that each time that there was an investment in a new (deeper) well, it also was necessary to change for a new pump that matched the well deepness and capacity. Deeper wells require bigger pumps.

Table 2. Overview of the scenarios evaluated with HELGA. With four scenarios comparing hydrological implications of recharge and adaptation strategies.

Scenario	Name	Recharge and green water use	Savings	Adaptation
0	Race-to-the-bottom	Excluded	3-year cost equivalent	No crop change
1	No-adaptation	Included	3-year cost equivalent	No crop change
2	Proactive	Included	3-year cost equivalent	Crop change only at investment
3	Proactive + Reactive	Included	3-year cost equivalent	Crop change at investment and in case crops are not profitable in a moving average of three years.

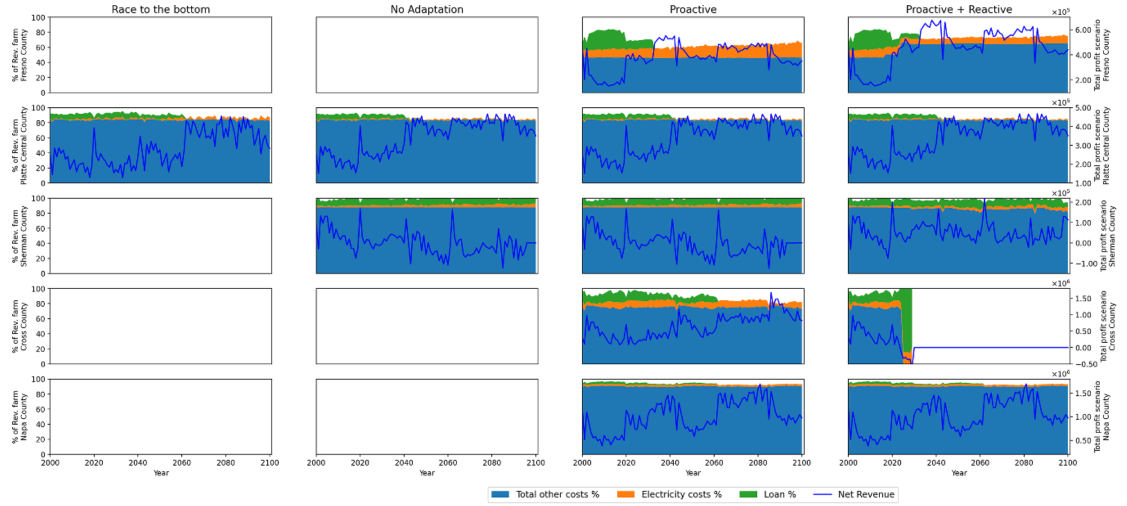

Figure 4. Stacked area (left-hand axis) of the other cost, electricity cost and loan payment as percentage of the gross revenue, and the total annual profit of the farm in USD/year (blue line, right-hand axis). Only one farm is profitable without recharge, two if recharge is allowed but no crop change is considered. The implementation of adaptation strategies ensures that all five farms become profitable.

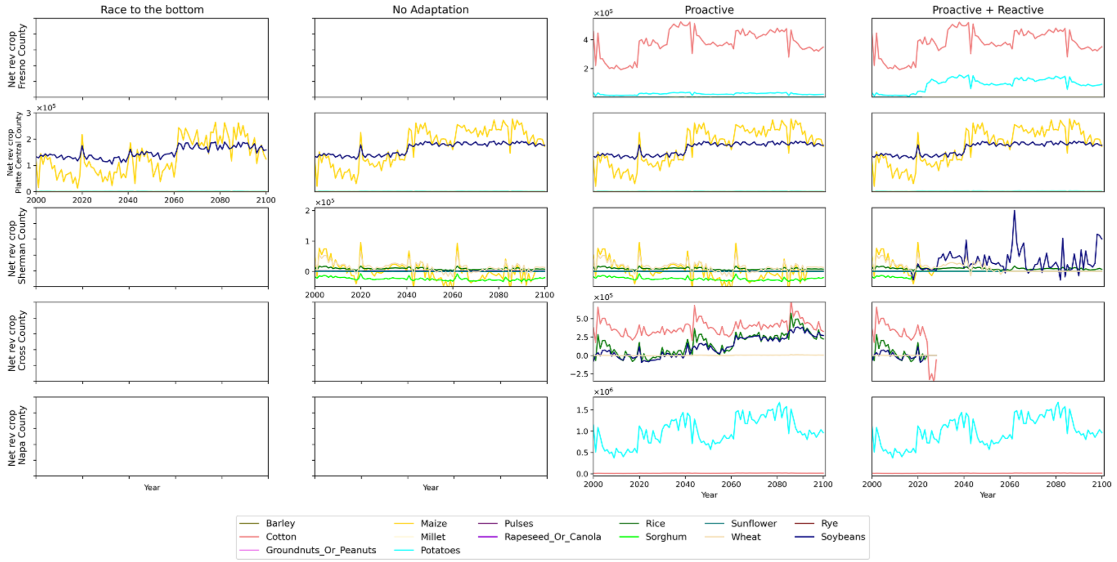

Figure 5. Net revenue per crop in USD/year at the five locations for the four scenarios. The crop mix only include cereals, roots and oil crops. The implementation of the crop mix as adaptation strategy is shown in the increase of area and revenue in crops like potato, cotton and soybeans.

removing crops that temporarily underperform. Conversely, eliminating consistently underperforming crops in the long term can enhance overall profitability. Thus, the scenarios demonstrate that the model effectively conveys the economic aspects of decision-making, distinguishing between short-term and long-term analyses. This capability will be instrumental in understanding different types of behaviour among farmers when subject to external factors such as climate variability or climate change, or perturbations in the economic market, and how this affects their ability to cope through different adaptation strategies.

4. Discussion and conclusions

In this study, a newly developed microeconomic heuristic model at farm level HELGA was introduced and applied to five farms with groundwater-fed irrigation in the conterminous USA. We used HELGA to evaluate the economic viability of the farms in light of the year-to-year variability in yields and crop water requirements and considered possibilities for adaptation and decision-making from the farmer's perspective.

Scenarios (table 2) highlight the importance of recharge in the hydrological system and its impact on economic performance. Adaptation by changing crop types and reducing crop areas, transitioning to more water-efficient crops, show positive results under the range of hydroclimatic conditions of CONUS. Short-term adaptation versus long-term adaptation yields mixed results: generally, profitability increases but shorter term negative crop yields can lead to a lock-in and result in a loss of profitability as was the case for Cross (figure 4). These findings provide insights on the viability of farmers' adaptation strategies, combining economic responses to hydrological impacts.

By focusing on the farm level, HELGA strongly emphasizes the local approach (Wing and Fisher-Vanden 2013). Also, traits can be assigned to the farmer, and decision-making has a heterogeneous scope, combining decisions on investment with crop selection aimed at increasing the revenue and reducing water cost (Keppo *et al* 2021). Even in this study, which imposed uniform behaviour to the farmers at the five locations, they adapted differently to the local conditions on the basis of past performance, which fits well in the concept of bounded rationality (Berrang-Ford *et al* 2011). Future work in which farmers are assigned traits and their behaviour emerges as a result of their agency will allow us to investigate feedbacks within the physical and socio-economic environment of figure 1 in which farmers operate, including their response to climate change.

The dependency of farmers on the hydroclimatic conditions, and in prominence of recharge, underscores the connectivity between the physical environment and the local economy, with repercussions for water resource management and environmental and financial sustainability. Feedbacks, therefore, are essential and these will appear prominently when HELGA is coupled to dedicated models for groundwater hydrology, crop growth, and price-effects through markets. In turn, HELGA adds the farmer's perspective to the simulations and his scope for adaptation. The need to cover this aspect is urgent as irrigated agriculture puts large claims on the available water resources on the one hand but is essential for securing the world's food supply on the other.

HELGA also highlights the vulnerability of farming systems. The scenarios underline how important it is to be able to absorb variability and shocks. Savings are important and remove the dependency on loans at most farms. Savings will become particularly important as buffer if market volatility is introduced. It also underlines the strategic importance of financial resilience in dynamic and/or transitioning agricultural landscapes.

To deal with changing hydroclimatic conditions and the increased costs of groundwater pumping, farmers have to adapt. In this study, we gave farmers the opportunity to change crop types, to invest in groundwater-fed irrigation or to divest by fallowing. Selecting more profitable forms of irrigation is something to explore in greater depth. It requires the consideration of irrigation water from other sources and the associated costs. In this way, impacts of changing environmental conditions and of fluctuations in regional and global markets can be assessed. HELGA provides a first step towards an integrated assessment from the farmer's perspective in which adaptation strategies can be considered to find positive trajectories to ensure economic viability and environmental sustainability of irrigated agriculture in the long run.

This paper presents a first application of HELGA to a limited number of farms to clarify the implications of the model concepts on the decision-making and adaptation that farmers have to consider to keep groundwater-fed irrigation profitable in the long run. Our next paper will apply HELGA fully coupled with PCR-GLOBWB and MODFLOW for hotspots of groundwater-fed irrigation across the world. In this manner, the interactions between the surface water and groundwater system on the one hand, and the competition for water between agriculture and other sectors will be covered on the other. Thus, trade-offs be quantified when investment decisions from HELGA are fed back into the hydrological simulations. As the hydrological simulations provide a finer temporal scale, also estimates of (rainfed) crop yields can be improved and will short-term variations in the irrigation water demand be represented in more detail. The application of HELGA over the contiguous areas of the hotspots and over the historical period will also provide an opportunity for a first validation of the performance of the model in terms of groundwater pump rates, yields and revenues. HELGA simulates individual farms and covers the full diversity in farm management. This makes it challenging to compare its outcomes with real data, given that farmers are heterogeneous in their responses to economic losses and their behaviour also results from other considerations than the economic ones covered by HELGA. However, as a population, farmers will show certain tendencies in their adaptation that can be compared to the projections made by HELGA as part of the validation.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.12668956. Data will be available from 02 November 2024.

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