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Improving water policy analysis in CGE models: Deriving substitution elasticities from biophysical crop data in a case study for Egypt

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A key challenge in modeling water scarcity in computable general equilibrium (CGE) models is getting the substitution elasticity between water and the other inputs right. This paper develops a novel method to derive the values of the substitution elasticity between water and land by implementing a one-way bottom-up linking from a crop model into a CGE model. Using biophysical relationships from a crop model, we calibrate the shape of the production function of agricultural activities in the CGE model. Furthermore, crop water requirement coefficients are imposed as biophysical constraints on the substitution in crop production. To demonstrate the advantages of this approach, we apply it to an irrigation water tax shock using SAM data for Egypt 2019 and compare the impacts under these derived elasticities with the elasticities of the GTAP-W model. The results show that our approach is similar to that of GTAP in the short run. However, in the long run, we find that the impact of the policy on agriculture is larger under the novel approach than under the GTAP elasticities. This method could be applied to other cases using region-specific crop model parameters to study water policy, water use efficiency, agricultural production, and rural development.

JEL: Q25, C68, Q18, Q12, Q15

Keywords: Linking, irrigation, crop water requirement, CGE model, water economics, elasticity

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1 Introduction

Ex-ante economic analysis of policy effect on the economy is usually done using either partial equilibrium or general equilibrium models (Burfisher, 2021). In both cases, the production function of each sector is defined as a nested structure in which inputs that are deemed substitutes or complements to each other are used in the same nest. One then proceeds by studying the impact of a change in a parameter, for instance, a tax on the economy or a specific sector of the economy. The results are highly sensitive to these nesting structures and how much one can substitute between two or more inputs in production.

In agricultural production functions, water is an important input. The impact of water scarcity and water policies on agriculture and the broader economy has been studied extensively in computable general equilibrium (CGE) literature (Calzadilla et al., 2011; Roson and Damania, 2017; Berrittella et al., 2007; Osman et al., 2016; Briand et al., 2023). This literature shows a mixed picture of policy impacts. Using the GTAP CGE model, Roson and Damania (2017) show that reallocation of water to more productive sectors could cushion some of the negative impacts of water scarcity in many regions of the world. Gómez-Limón and Riesgo (2004) on the other hand show that market-based water allocation benefits the economy as a whole while it harms agriculture in the Balearic Islands. Using a national CGE model for Morocco, Diao et al. (2005) suggest that water markets increase agricultural output. Ponce et al. (2012) provide a review on modeling water in national and global CGE models.

While for the production factor land, the need to implement biophysical constraints in economic models has been recognized and implemented (see, for instance, Taheripour et al., 2020; Delzeit et al., 2020), integrating biophysical constraints into general equilibrium models studying water issues is still lacking. Another closely related challenge is modeling the elasticity of substitution between water and non-water inputs in production. These two factors determine to a great extent the response of agents to water management interventions. For example, advanced irrigation technology (e.g. drip irrigation, sprinkling irrigation) allows farmers to reduce their water use without sacrificing yield. Ignoring this, models might return misleading results.

In the GTAP-W model, for example, region-specific elasticity values (ranging from 0.04 to 0.14) are used for the substitution between water and land (Calzadilla et al., 2011). This elasticity is derived using the price elasticity of water demand (Rosegrant et al., 2002). However, in many regions of the world, irrigation water is not priced, or if it is priced, the prices do not vary enough to allow such estimation. Other models use land and water in fixed proportions (see, for instance, Dixon et al., 2009; Robinson and Gehlhar, 1995). Advancements in irrigation technology suggest that substituting water and non-water inputs might be feasible. However, water is not quite the same as capital and labor in the sense that there are limits to substituting it with other factors in production. Particularly in agriculture, water cannot be replaced below a specific level regardless of how much of the other inputs are used. This is not just a technical constraint as in the case of capital and labor, but it is a natural biophysical constraint.

In this article, we take this into account and allow for substitution between land and a composite water nest under the imposition of a biophysical constraint. Furthermore, we derive these elasticities by linking the IFPRI CGE model to the PROMET crop model instead of using the price elasticity of water use as in Calzadilla et al. (2011).[1] The biophysical crop model PROMET calculates the yield-water relationship for Egypt. An extended version of the CGE model is then calibrated to Egypt's SAM data 2019 using the linking-based elasticities developed here. The country is a leading example of how water scarcity can restrict economic activity, especially in agriculture. Then, we run a water tax simulation where the value of the tax is calculated using the endogenous change in the shadow price of water. The results show the impact of the price shock on real agricultural GDP and total GDP among other variables of interest. To demonstrate how sensitive the model results are to these conditions, the simulation is run using GTAP-W elasticities with and without biophysical constraints and is compared to the case where the same policy is implemented using the linking-based approach developed here.

The findings show that our approach yields results comparable to GTAP under the assumption of fixed factor supply and immobile capital (short-run closure). In contrast, running the simulations with more factor adjustment possibilities (long-run closures), the new method generates effects of the shock on agriculture and overall GDP that run counter to those produced using GTAP elasticities.

We make two main contributions to the literature on water economics and model linking. First, we derive a theory-based water price curve as a function of water scarcity. This price is used as a water tax in the simulation. This has the advantage of creating a benchmark (optimal pricing rule) against which any other policy could be compared. Second, we link the CGE model to a crop model. The crop model provides two services to the economic model. First, it informs the CGE model about crop-specific minimum water requirements, which is a main parameter in the CGE model. Second, we use the yield-water relationship from the crop model to calibrate the elasticity parameter of the land-water relationship of each crop.

The rest of the paper is organized as follows, Section 2 presents the standard model and the modifications, and outlines the data, Section 3 describes the scenarios and the closure rules, Section 4 presents the results and discusses their implications, and Section 5 concludes.

2 Methods and data

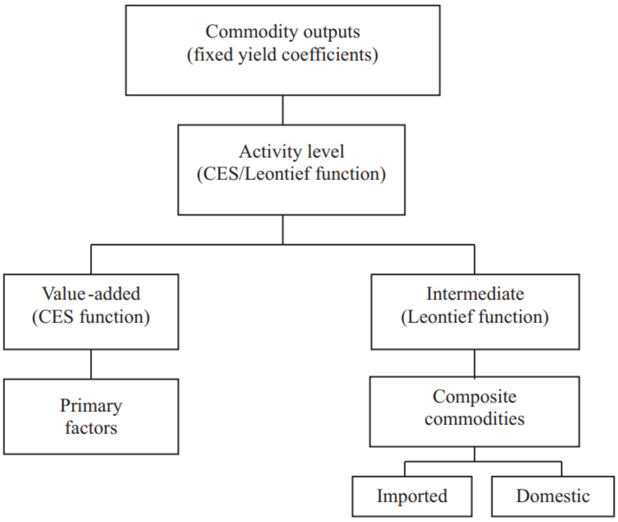
Given the size of the agricultural sector in Egypt, the intersectoral relationships and the fact that water enters the production in almost every sector, a general equilibrium model is used. CGE models capture the competing use of water in the different sectors and therefore are suited to study policies that have economy-wide impacts. The model we use in this study is an extended version of the IFPRI standard model. The model is written and solved using the General Algebraic Modeling System (GAMS) as a non-linear system of equations.

[1]This is the one-way bottom-up linking. One way because the linking goes in one direction. Bottom-up means that we use the more disaggregated model, in this case, the crop model, to inform the more general model, the CGE model, about the values of parameters that are not explicitly modeled in the CGE model. For more on the different approaches of model linking, see Delzeit et al. (2020).

2.1 The IFPRI standard model

The International Food and Policy Research Institute IFPRI model is a static single-country model. It describes production, consumption, and trade as a solution to a set of optimization problems for each representative agent in the model. A set of endowment and income constraints apply to the economy as a whole. Representative households consume according to a Stone-Geary demand function with commitment terms (subsistence level of consumption).[2] On the production side, the output is produced by combining intermediates and value added according to a constant elasticity of substitution (CES)/Leontief technology (Figure 1). In the value-added nest, all primary factors are substituted according to Cobb Douglas. Water in the standard model enters the intermediates composite and is used with other inputs in this nest in fixed proportions. Trade with the rest of the world is governed by Armington elasticities. The standard model is described in detail in Lofgren et al. (2002). The rest of the method section will discuss the new features we add to this standard model in addition to the linking with the crop model.

Figure 1: Standard IFPRI model production function (Lofgren et al., 2002)



2.2 Water Production

One of the extensions introduced into the standard model here is the explicit modeling of the water-producing sector. To avoid confusion about the terms related to the water sector, we start by defining them. The water resource is a primary factor. In order for it to be used by agriculture or as potable water, it needs to be pumped, processed (in the case of potable water) and delivered by the water activity using capital, energy, labor, etc. The product of this process is the water commodity which comes in two different qualities

[2] The demand function in the Linear Expenditure System (LES) is a generalization of the Cobb Douglas. The utility function takes the form $U = \prod_{i=1}^{n}(x_i - \gamma_i)^{\alpha_i}$, where γ_i denotes the subsistence level consumption of good i. This is the share of consumption that does not respond to changes in the price of commodities. α_i denotes the expenditure share of good i beyond the subsistence level. The resulting Marshallian demand is given as $x_i = \gamma_i + \frac{\alpha_i}{p_i}(y - \sum_j^J p_j\gamma_j)$ where $i \in J$ and γ_j is the demanded subsistence quantity of good j.

(sub-commodities), low-quality water commodity used by agriculture (irrigation water), and high-quality water commodity used by households, industries, and services (urban water). Effective water is the combination of irrigation water and irrigation capital. In particular, it is important to note that irrigation water is not the same as water resource.

Figure 2: Water production and consumption in the extended model

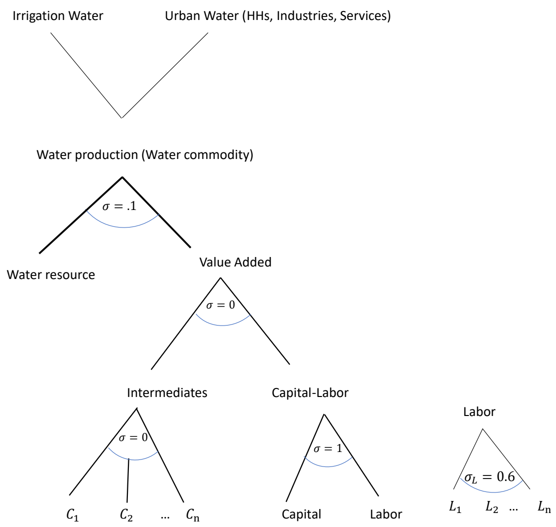


Figure 2 illustrates the structure of water production and consumption. To produce the water commodity, the water-producing activity needs water resource as well as a composite of all other factors and inputs. Some substitution at this level is allowed to reflect the possibility of efficiency improvement on the supply side. In water-scarce settings, water has a value in its raw form (water resource). The delivery of water commodity contains many deficiencies related to leakage and lack of investment which, if addressed, could help mitigate these issues (Abdin and Gaafar, 2009). In Figure 2, an elasticity of 0.1 between the water resource and the VA nest is specified. When water scarcity increases, it is possible to invest more in the water delivery infrastructure (capital and other inputs) to reduce losses. However, a limit to this substitution is imposed through a physical constraint which puts an upper bound on supply side loss reductions to ensure that water production cannot increase unboundedly just by investing in infrastructure. The implemented upper bound states that the amount of water produced cannot increase by more than 10% keeping the water resource fixed.

The water commodity is used in different degrees of quality, e.g., irrigation vs. potable water. To capture these aspects, a water commodity with two different qualities is created. Thus, a quality-adjusted price of water is calculated as follows:

$$p^w(q) = \overline{p^w}\ k_q, \qquad q = \{High, Low\} \tag{1}$$

Where $\overline{p^w}$ is the average water price and k is an adjustment factor for quality type q. Consequently, there is low-quality water that goes to agriculture and high-quality water that goes to all other uses. Section 2.7 below illustrates how this method is used to create quality-adjusted prices p^w for water in agriculture and non-agriculture. As a result, the baseline price of irrigation water is 0.12 and the high-quality water price is 1.7 units of local currency.

Further, the nesting keeps the transformation relationship to allocate water between agriculture and non-agricultural uses flexible, since we lack any information about this relationship. This flexibility allows the allocation to be determined by competitive forces. As in the standard model, the water commodity enters the utility of households according to the Stone-Geary demand system. Non-agricultural sectors (industries and services) use water as an intermediate with fixed coefficients. Now we turn our attention to the use of water in agriculture, where the main modifications to the standard model are introduced.

2.3 Water use in agriculture updated

Irrigation water is used as input in a multilevel nested production function. Figure 3 illustrates the full nesting structure in the extended version of the IFPRI model for agricultural sectors. In this section, we highlight the main extensions introduced to the model.[3]

Farmers choose the quantity of irrigation water to maximize their own net benefits. The choice is twofold. The first level is how much water to use for a given crop. Second, one has to decide how much irrigation technology to use, that is, flood irrigation versus advanced irrigation. In the first level of choice and due to the open access nature of the common resource, the optimal choice of water use from an individual's perspective is higher than that of the social optimum. The derivations of the results used in this section are given in Appendix A.

The second decision is how much to invest in irrigation capital – the water-saving technology applied at the farm level, such as drip irrigation. Irrigation capital helps reduce excessive water use without sacrificing yield. For a given yield level, an irreducible amount of water $\underline{\mathrm{w}}$ is needed. This is obtained from the biophysical crop model for each crop and for each yield level, as explained in Section 2.5 below. This relationship is depicted as:

$$w = \underline{\mathrm{w}} + h(u, K) \tag{2}$$

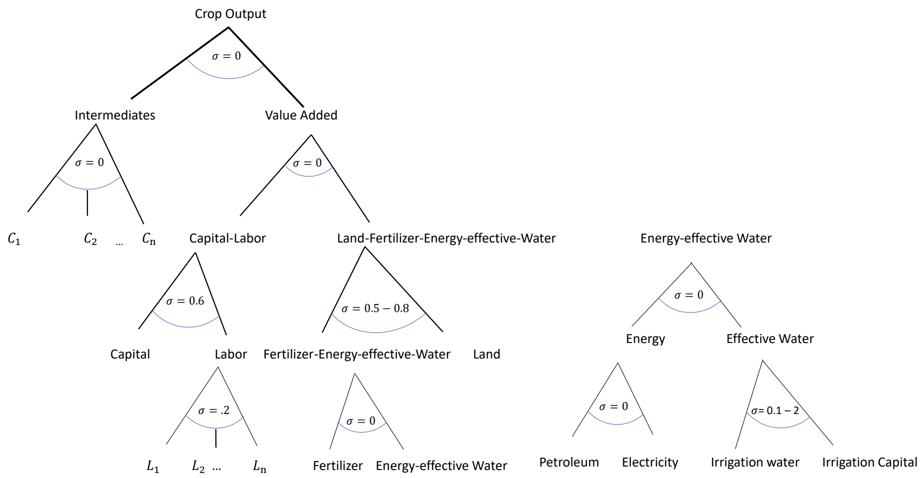
where w denotes the effective water, h is a function that defines the substitution possibility between irrigation capital K and residual irrigation water, u – the water applied beyond what is needed. This residual water does not contribute to the yield and does not generate any economic value. However, it can be reduced only if irrigation capital K is used to deliver irrigation water. The cost minimizing behavior results in optimal investment in irrigation capital given by (see Appendix A):

$$\frac{u}{K} = \left(\frac{\delta}{1-\delta}\,\frac{r}{p^w}\right)^{\sigma}, \qquad \sigma > 0 \tag{3}$$

Where r is the rental price of irrigation capital, p^w is the optimal price of irrigation water that includes the value of the water resource and the other cost of delivering the

[3]The complete extended model is available upon request.

Figure 3: Nested Production function for crop production in the extended model



irrigation water commodity, σ is the substitution elasticity between irrigation and irrigation capital, and δ is the baseline input value share of residual irrigation.

Under water scarcity conditions, the absence of markets and the open-access nature of water lead to an equilibrium where water use is inefficient. Introducing a price to reflect the social costs of this resource would lead to an improvement in the total welfare of society. The mechanism that drives this in our model is the reallocation of water toward more productive uses and water saving. The allocation observed in the baseline data (underpricing and no inclusion of the value of water resource), especially in agriculture, favors those who have advantageous access to irrigation water which prevents more productive water uses from being realized, and thus the inefficiency. It is well known in the literature on irrigation systems that this is caused by the so-called head-enders, tail-enders *asymmetric commons dilemma* (Janssen et al., 2011).[4]

2.4 Value of water resource

Since including the value of the resource in the price of the water commodity is important, Appendix B illustrates how this value is determined. These results show that the value of water used in production is a function of water supply (scarcity effect), output level (scale effect), and substitution between water and the other inputs (technical effect).

[4] In the standard common dilemma all members of a society or group who share a common resource have equal access to the resource. In other cases however the members have different access to the resource. Irrigation water is a standard example where the access to the common resource is determined by the location of the land on the irrigation facility. Upstream water users (head-enders) would have more advantageous access and can overuse the resource to the disadvantage of those whose location is downstream (tail-enders).

$$\lambda(\bar{W}, Y) = c\left(\frac{Y}{\bar{W}}\right)^{\frac{1}{\sigma}} - c^{w} \tag{4}$$

Where $\bar{W}$ denotes the total supply of the water commodity, Y is total output, c is a constant, and c^w is the unit cost of other inputs. By Equation (4) the value of the water resource λ increases with expanding output and shrinking of the water supply.[5] However, the curvature of λ depends on the interaction of these effects as given in Appendix B. In Section 3.1 we test this in the data to see how the value of water resource changes when we exogenously change its supply. It turns out that the same relationship is observed in the SAM data for Egypt. This means that the value of the water resource changes at an increasing or decreasing rate and the global curvature is undetermined.

The economic interpretation of this result is that the rate at which water prices increase – whether it is accelerating or decelerating – is determined by the complex intersectoral interactions within the economy given the exogenous parameter σ. In fact, there are two main effects. First, the decline in water supply raises the water price. The second effect is that the decline in water supply depresses the total output, which in turn reduces the demand for water, and therefore the water price declines. The general equilibrium effect is the sum of all these interactions.

2.5 The crop model

To depict the relationship between crop yields and irrigation water requirements for Egypt, we apply the biophysical crop model PROMET to maize, rice, and wheat crops in 0.5° spatial resolution (Mauser et al., 2015; Zabel et al., 2019; Jägermeyr et al., 2021; Müller et al., 2021; Schneider et al., 2024; Müller et al., 2024)

The PROMET model is driven by ATTRICI v1.1 counterfactual climate data for the time period 1901 – 2019 for the global observational reanalysis dataset GSWP3-W5E5 (Mengel et al., 2021). The counterfactual climate removes long-term trends from climate but retains inter-annual climate variability of the reanalysis data. The sowing dates for Egypt are taken from (Jägermeyr et al., 2021) and are kept constant over the time period. We apply crop-specific historical inputs as a sum for nitrogen fertilizer, manure application, and atmospheric nitrogen deposition (Volkholz and Ostberg, 2022), which start at low values below 10 kg/ha in 1901 and increase almost linearly for all considered crops from 1945 onward, reaching over 350 kg/ha for wheat after 2010 (see Figure E3 in the Appendix). Thus, a broad range of different nitrogen inputs from very low to high values are considered in the simulations, which drive the increasing water demand of the crops following Liebig's law of the minimum. This means that agricultural crops cannot convert more water into more biomass and yields if they are nutrient-limited. Vice versa, crops with a sufficient supply of nutrients need more water. The simulations are performed separately for rainfed and fully irrigated conditions. For the latter, we assume no water restrictions. As a result of these simulations, we obtain agricultural yields (fresh

[5] The relationship between λ and σ is found by differentiating Eq. (4) w.r.t. σ to get $\frac{d\lambda}{d\sigma} = -\frac{\log(Y/\bar{W})}{\sigma^2}\left(\frac{Y}{\bar{W}}\right)^{\frac{1}{\sigma}}$. Due to the appearance of the logarithmic term on the right hand side, the sign of the change in λ is determined by the inverse of the average water intensity in the economy $Y/\bar{W}$. If this term is greater than 1 meaning that the average water intensity in the economy is less than 1, then $\frac{d\lambda}{d\sigma} < 0$.

weight of harvested fruit biomass in t/ha) and daily transpiration rates for the selected 3 crops, separately for rainfed and irrigated conditions, for a time series of 120 years at a constant long-term but variable annual climate, as well as continuously rising fertilizer rates. This results in variable agricultural yields, which are achieved under different annual climatic conditions and different fertilizer levels. The irrigation water requirements $\underline{w}$ are calculated as follows:

$$\underline{w} = t^{ir} - t^{rf} \tag{5}$$

where t^{ir} is the crop's cumulative daily transpiration (mm) over the growing period (from sowing to harvest date) for fully irrigated conditions, and t^{rf} for rainfed conditions. Thus, the calculated irrigation water requirements show the additional amount of water used (transpired) by the respective crop without water limitation. Thereby, we assume optimal irrigation practices without evaporative losses or water percolation, which is a theoretical optimum or a potential for the minimum additional amount of required irrigation water to obtain a certain yield under irrigation practices. The natural conditions, including the amount of precipitation, soil type, evaporative losses, and losses due to interception of precipitation, are considered by the crop model. Finally, for each crop, we consider all pixels for Egypt with a harvested rainfed and irrigated area (Portmann et al., 2010). Due to the continuous increase in fertilizer application from 1901 to 2019, crop yields and irrigated water demand increase strongly over time (see Figure 4). For the relationship between yield and irrigation water requirement, we estimate:

$$y = a + b\underline{w} + \epsilon \tag{6}$$

The relationship between yields and irrigation water requirements is shown in Figure 5 as a scatterplot, together with the linear regression model obtained for all simulated crops. The coefficients of the linear regression model and their quality are given in Table 1. The crop model does not provide data for all the crops considered in the CGE model. For sugarcane, because it is a C4 crop like maize, which implies that they have a similar water use efficiency profile, we use maize as a proxy crop. For vegetables, fruits and the aggregate of other crops, the average over wheat, rice, and maize is used.

In the PROMET model, we assume perfect irrigation without any water loss. Consequently, the water consumption due to irrigation is a theoretical value that can only be reached under optimal management conditions and must be interpreted as a minimum amount of water that is required to obtain a certain yield. As a result, this assumption tends to underestimate water demand in comparison to reality due to inefficiencies in current irrigation practices. The reasons for current inefficiencies are manifold and include, for example, losses during transport of water through open or fragile channels, the use of inefficient technologies, such as flood irrigation instead of subsurface drip irrigation (SDI), which applies exactly the required amount of irrigation water directly to the root zone, thus reducing evaporative, lateral, or percolation losses.

2.6 Linking the economic model to the biophysical crop model

After setting up both models, the next step is to use the crop model information as input and as a constraint on the economic model. The minimum requirement estimated by the biophysical model $\underline{w}$ from Eq. (6) is used for two purposes in the CGE framework.

Figure 4: Relationship between irrigation water requirements and simulated yields for the 1901 – 2019 time period, exemplarily shown for maize. A z-transformation is applied to the data due to unequal units

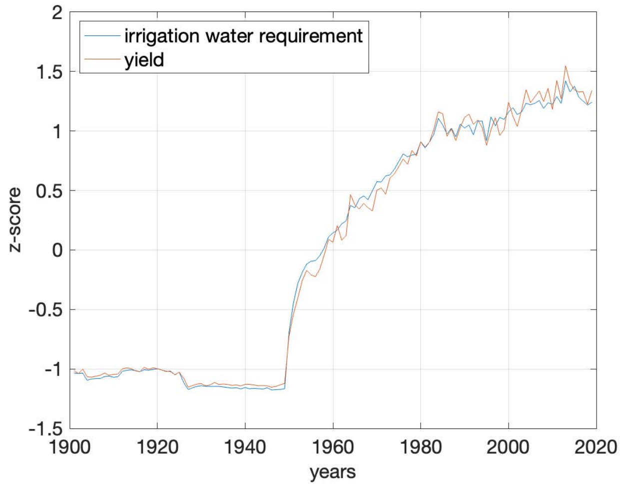
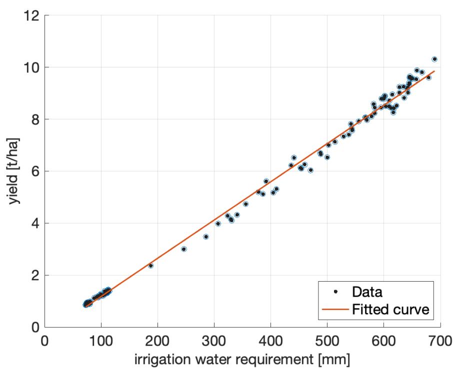
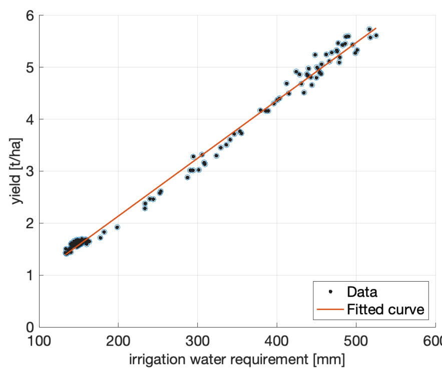


Figure 5: Relationship between simulated irrigation water requirements (in mm) and yield (in t/ha) for a) maize, b) rice, and c) wheat. The fitted linear regression line is shown in red.

(a) maize



(b) rice



(c) wheat

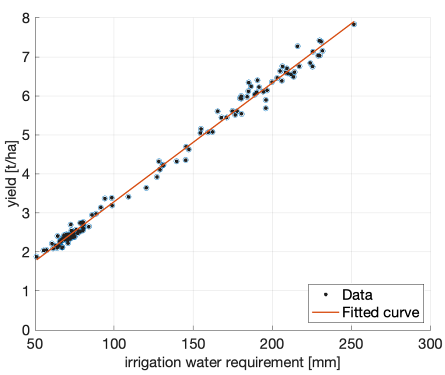


Table 1: Coefficients of the linear regression model ($y = a + b\underline{w} + \epsilon$) between irrigation water requirement (in mm) $\underline{w}$, and yield (in t/ha) y.

Crop	a	b	t-value	R^2
Maize	-0.29000	0.01650	140.67	0.996
Rice	-0.01773	0.01149	189.77	0.994
Wheat	0.49263	0.03004	29.183	0.993

First, the minimum water requirement for different crops is used to define the level of substitution between irrigation water and water-saving technology (irrigation capital). Implementing this as a biophysical constraint is important because it limits the possibility of substitution. That is, for any given level of yield, there is a minimum amount of water that has to be delivered to the plants. Thus, for each crop, the following biophysical constraint is imposed:[6]

$$\frac{Irr.Water}{LAND} \geq \underline{w}^0 \frac{y}{y^0} \tag{7}$$

Where the left hand side is the irrigation water by unit of land, $\underline{w}^0$ is the water requirement in the baseline, and y and y^0 denote the yield level and the yield level in the baseline, respectively.[7] Thus, the right hand side is the yield-adjusted minimum water requirement. This allows irrigation to be replaced by the technology in the lower nest of Figure 3 up to a specific level that cannot be crossed. This constraint is crop specific. Second, the CGE model includes an equivalent for the crop model yield water relationship.

In the CGE model, a strictly concave relationship between yield and effective water (compared to water consumption $\underline{w}$ in the crop model) is assumed – to ensure diminishing marginal returns of each input. Linearity would suggest that the inputs are perfect substitutes, which is not an appropriate way of modeling this. Consequently, the CGE model defines the yield as follows:

$$y = f(w, \mathbf{x}) \tag{8}$$

where $\mathbf{x}$ is a vector of all other inputs. In addition, we can write the relationship between $\underline{w}$ and effective water w as follows:

$$\underline{w} = \kappa\, w, \qquad 0 < \kappa \leq 1 \tag{9}$$

where κ measures irrigation efficiency. Using available data on irrigation water withdrawal by crop (CAPMAS, 2019), we calculate κ for each crop. Substituting Equation (9) into Eq. (8) gives:

$$y = f\left(\frac{\underline{w}}{\kappa}, \mathbf{x}\right) \tag{10}$$

[6]This constraint is imposed in GAMS through lower bound as following:
IRRInt.lo(a) = IRRInt_min(a)*Yield_Rel.L(a);
where IRRINT is Irrigation Water/LAND, $IRRInt\_min$ is $\underline{w}^0$, and Yield_Rel is Yield/Baseline Yield and a denotes the set of crops.

[7]In the baseline y and y^0 are the same. In the simulation, y might deviate from the baseline level y^0, however.

By specifying f as a CES we can write:

$$y(w, \mathbf{x}) = \alpha \ \left(\delta \ w^{-\rho} + (1-\delta) \ \mathbf{x}^{-\rho}\right)^{-\frac{1}{\rho}} \qquad \rho \neq 0, \rho > -1 \tag{11}$$

Using the crop model relationship, Eq. (6), the percentage change in yield for each percentage change in water consumption is:

$$\frac{dy}{d\underline{\mathrm{w}}}\frac{\underline{\mathrm{w}}}{y} = b \ \frac{\underline{\mathrm{w}}}{y} \ = \ b \ \kappa \ \frac{w}{y} \tag{12}$$

In the CGE model we can calculate the change in yield with respect to the change in effective-water (in percent) as:

$$\begin{aligned} \frac{dy}{dw}\frac{w}{y} &= \alpha^{-\rho} \ y^{1+\rho} \ \delta \ w^{-\rho-1} \ \frac{w}{y} \\ &= \delta \ \alpha^{-\rho} \ \left(\frac{w}{y}\right)^{-\rho} \end{aligned} \tag{13}$$

Now, the goal is to bring the changes in yield due to changes in water consumption of both models closer to each other. In essence, we ask the following question: what value of elasticity between land and the composite of Fertilizer-Energy-effective-Water would make the change in yield due to the change in effective water in the CGE model similar to that of the crop model keeping the other elasticity parameters fixed. What makes this possible is that both the crop model and the CGE model have this relationship between yield (output per unit of land) and water consumed. It is important to note that the yield changes only if the effective water changes (the combination of irrigation water and irrigation capital). That is, any change in irrigation water or irrigation capital which keeps effective water unchanged does not affect the yield . Mathematically, one needs to solve:

$$\min_{\rho} \ \sum_{m} \left(\delta \ \alpha^{-\rho} \ \tilde{w}_m^{-\rho} \ - \ b \ \kappa_m \ \tilde{w}_m\right)^2 \tag{14}$$

where $\tilde{w}_m$ is defined as the effective water by unit of yield w/y and m defines the value of the parameter at a specific level. For instance, $m = 0$ would be the baseline quantities of effective water and yield. Equation (14) is a non-linear programming problem where the elasticity exponent ρ is the choice variable which is crop-specific. The first order condition is given by:

$$\frac{d}{d \ \rho} = \alpha^{-\rho} \ \tilde{w}_m^{-\rho} \ \left(\log \ \alpha + \log \ \tilde{w}_m\right) \ \sum_{m} \left(\delta \ \alpha^{-\rho} \ \tilde{w}_m^{-\rho} \ - \ b \ \kappa_m \ \tilde{w}_m\right) = 0 \tag{15}$$

Since this problem has no closed form solution it needs to be solved numerically. The procedure we introduce here is as follows:

1. Starting with any arbitrary value of ρ (within its defined domain) for each crop, calibrating the CGE baseline according to Eq. (11) (or its equivalent depending on the nesting structure) generates the baseline values of the parameters. We used the substitution elasticity between irrigation water and irrigable land of the GTAP-W model as our stating point.

2. After calibrating the baseline, to generate additional values, we run a simulation in which the total irrigation water supply is reduced stepwise by 2% and generate 25 scenarios. As a result, 25 different levels of effective water use and the corresponding yield levels are obtained.
3. In a separate GAMS file, inserting this information into Eq. (14) or equivalently, Eq. (15) gives the value of ρ.
4. Then this value has to be inserted back into the CGE model as the new starting point and repeat steps 1 to 3.
5. Repeat this exercise until the value of ρ ceases to change.

Using this approach, we find the optimal value for ρ that uniquely solves Eq. (15). Table 2 presents the resulting values for $\sigma = 1/1 + \rho$ from this procedure for each crop where σ corresponds to the substitution elasticity between land and the composite of Fertilizer-Energy-effective-Water in Figure 3. Column 2 presents the values used in the GTAP-W model for the substitution between water and land (Calzadilla et al., 2011). GTAP elasticities are based on the estimate of the water demand elasticity taken from Rogers et al. (2002). Appendix C explains the method used to derive the elasticities of the GTAP-W model and our comments on the limitation of the approach. We show in particular that the value of elasticity in GTAP-W does not account for general equilibrium effects of factor price change. Furthermore, we show that the GTAP-W elasticity is not constant.

The elasticity based on the current approach is significantly higher than the one used in the GTAP-W model. The simulation that generated our results in column 3 is based on flexible factor supply and factor mobility, meaning that one needs to think of these elasticities rather as medium to long run elasticities.

Table 2: Elasticity of substitution between land and Fertilizer-Energy-effective-Water composite

	σ in the GTAP-W model	σ from the current approach
Maize	0.08	0.50
Rice	0.08	0.52
Wheat	0.08	0.72
Sugarcane	0.08	0.78
Vegetables	0.08	0.79
Fruits	0.08	0.68
Other Crops	0.08	0.64

Note: The GTAP values (column 2) correspond to North Africa region in GTAP database. The values from linking-based approach (column 3) are specific to Egypt.

2.7 Social Accounting Matrix for Egypt 2019

The modified version of the model is calibrated to the Social Accounting Matrix (SAM) for Egypt for 2019 (Serag et al., 2021). The original SAM comprises 69 activities and 73 commodities. This includes 14 crop categories, five livestock sectors, and 16 food processing and processing activities of agricultural raw materials in addition to the manufacturing and service sectors. We aggregated the data into 17 sectors, in total, including 7 crops, 1 livestock, 1 sugar refining sector, and 1 food processing sector. The SAM also includes 8 different types of labor, 4 types of capital, and 10 households classified by 5 different income quintiles and urban vs. rural. Table 3 shows all activities (after aggregation) and their contribution to output, labor income, and consumption. The agricultural sectors account for 10% of the output and around 14% of both the labor income and the consumption. In addition, sectors closely related to agriculture, such as sugar refining and food processing industries, are important to the Egyptian economy.

The SAM includes an account for water and sewage commodity. This water is used by agriculture, industries, and households. The activity that produces this commodity uses intermediates and value added. We update the SAM by adding the physical quantities of the water resource compiled from (CAPMAS, 2019). Then we assign half of the value paid by water activity to the capital account as the value of the water resource.[8] The resulting calibrated unit price of the water resource in the baseline is 0.09 Egyptian Pound (EGP).

Finally, following the method described in Section 2.2 we create water with two qualities. The low-quality water commodity goes to agriculture and has a baseline price of 0.12 EGP per unit (=1 cubic meter), and high-quality water goes to other uses and has a price of 1.7 EGP in the baseline. The data for agricultural areas and irrigation water withdrawal are taken from CAPMAS (2019). Table 4 illustrates the SAM and the administrative data on water production and water use. The data on water requirement by crop is taken from the PROMET crop model.

The SAM does not include data on irrigation capital, an important input in the extended version of the model (see Figure 3). Fortunately, the FAO report (FAO, 2016) provides data on the area equipped with irrigation capital. To calculate the cost of irrigation capital, we use publicly available credit data (Elshorouk Daily Newspaper, 2021). Appendix D explains in length how the irrigation capital account is constructed and added to the SAM.

3 Simulation methodology and closure rules

3.1 Simulation methodology

The shock variable in the current analysis is the irrigation price. Due to the lack of market information on the value of the water resource, we calibrated the baseline value of the shadow price of the water resource as described in Section 2.7 to generate a baseline value. Assigning a value to this resource in the baseline is necessary in order to calibrate the model. As a result, we are able track the changes in the shadow price as a function of water supply and output according to Eq. (4). The changes in the shadow price compared to the initial value are generated by an experiment in which the total supply of water resource is reduced stepwise by 2%. Alternatively, one can fix the water supply and increase the size of the economy Y in Eq. (4) by exogenously increasing the endowments. The results of this shock are given in Figure 6.

Subsequently, these changes in the value of the water resource are used to construct the water tax simulation. Specifically, the simulation mimics an increase in irrigation price

[8] Imputing the initial value of the water resource from capital endowment is used in studies where no water resource account exist in the SAM initially (see for instance Faust et al., 2015).

Table 3: Descriptive statistics for Egypt's SAM 2019

	Share in output value	Share in labor income	Share in HH consumption
Maize	0.006	0.013	*
Rice	0.003	0.004	0.003
Wheat	0.002	0.002	0.005
Sugarcane	0.003	0.004	*
Vegetables	0.014	0.017	0.025
Fruits	0.012	0.025	0.019
Other-Agr.	0.009	0.017	0.011
Livestock	0.048	0.055	0.076
Total-AGR	**0.098**	**0.136**	**0.139**
Sugar refining	0.007	0.002	0.018
Food processing	0.062	0.021	0.128
Mining	0.066	0.03	0.017
Manufacturing	0.176	0.065	0.159
Electricity	0.028	0.011	0.037
Water	0.014	0.011	0.005
Petroleum	0.07	0.004	0.08
Fertilizers	0.007	0.002	*
Trade	0.078	0.089	0.018
Transport	0.056	0.125	0.085
Services	0.337	0.503	0.315

Note: Own calculations based on the Social Accounting Matrix for Egypt (Serag et al., 2021).
*: No final demand.

by adding the change in the value of the water resource as a tax on irrigation price. These tax values are introduced as a unit tax on irrigation quantity.

3.2 Closures

It is well known that the results of CGE models are sensitive to the closure rules (Hosoe et al., 2010). The closures determine how the macroeconomic variables that are assumed exogenous to the model are related to the model variables. For instance, if saving is not defined in the model in terms of agents' optimization behavior, then it becomes exogenous and has to be either fixed or it has to follow another variable, which in this case would be investment. Therefore, a careful choice of the closure environment that fits reality and helps to adequately answer the research question is necessary. In this sense, we motivate the choice of macroeconomic closures.

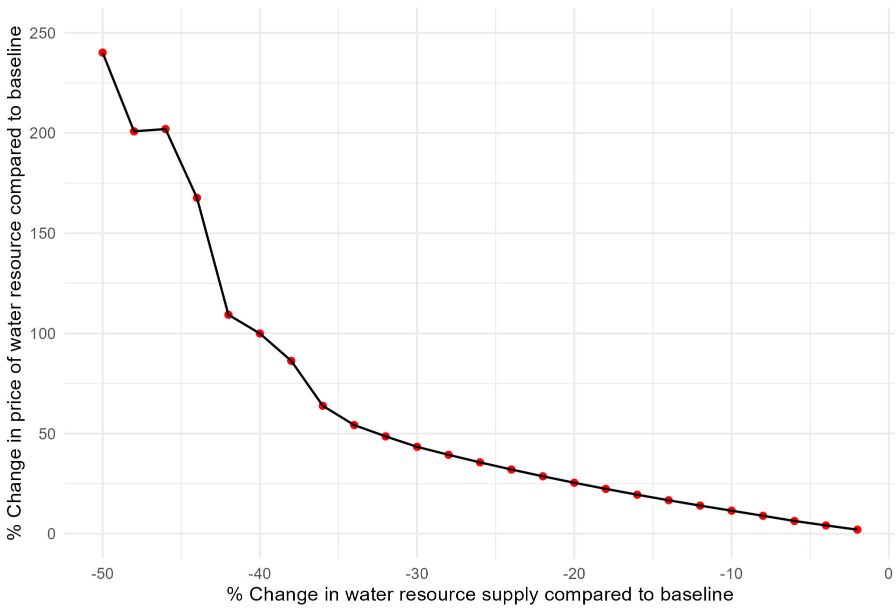
The government deficit is fixed. The rationale for this is that the water resource is modeled as a factor owned by households (the same as labor, capital, or land), while the tax payments are added to the government account. Consequently, under a water tax scenario, the income taxes paid by households will be reduced. This implies a full redistribution of the tax. Furthermore, this leads to avoiding misleading welfare gains by an increased government spending in a one-period static model like the one used here.

Table 4: Water production and water use by sector

Water Production			Water Consumption		
	Quantity	Value		Quantity	Value
Water resource quantity	77	7.1	Agriculture	100	12.2
Other inputs	48.6	48.6	Non-Agriculture	25	43.5
Total	125	55.7	Total	125	55.7

Note: Water quantities are taken from FAO (2016) and measured in billion cubic meter, whereas the quantities of other inputs and the values are taken from the SAM and given in Egyptian Pound (EGP). To convert to US$, a conversion factor of 0.06, the exchange rate (US$ EGP) at the end 2019) may be used.

Figure 6: Change in the shadow price of water resource compared to the baseline due to exogenous change in quantity of water resource from the CGE Model



The world price of each commodity is fixed. This is a standard small open economy assumption that fits the case of Egypt. For the balance of payments, a flexible trade balance is assumed, implying flexible foreign savings while the exchange rate is fixed. Fixing foreign savings would require fixing the real net exports, which would be inadequate when running shocks targeting the production side of a small open economy since these policies are expected to affect the trade balance.

For the saving-investment closure, investment as a share of total absorption is fixed at the base share, which implies that the saving rates adjust if needed to ensure that the ratio of investment level to absorption remains constant. For a detailed discussion of the closures (see, for instance, Hosoe et al., 2010).

The labor market closures are chosen to approximate the realities in the short and long term, respectively. The short run is defined by fixed factor endowments and immobile capital while keeping the other factors mobile across sectors. This means that changes can be attributed to the respective policy with no endowment effects. In the long run, we exogenously increase the endowment of all factors (except the water resource endowment) incrementally by a step of 2%, and all factors become mobile. To isolate the endowment effect from the policy effect, we run the long run with the endowment changes once with the tax policy in place and once without the policy. In this case, the reported policy effect is the difference between these two situations. According to this set up, the baseline in the long run is the economy under the endowment increase but without the policy.

In the short- and in the long run full employment is assumed, implying that factor prices are the market clearing variable. They adjust in the aftermath of any changes in market conditions to equate supply and demand. Finally, the CPI is used as the model numeraire.

3.3 Scenario description

The baseline price for one cubic meter of irrigation water is 0.12 EGP.[9] To define a price shock, we make use of the data on the global irrigation price which lies between 1 US cents/m^3 and 2.5 US cents/m^3 (Calzadilla et al., 2011). The price under the shock of 0.18 EGP is approximately 1.1 US cents/m^3 (without adjustment for inflation). This corresponds to a 50% increase in the price of irrigation water. In doing so, a counterfactual to the baseline is generated.

The policy is implemented under short and long run closures, respectively, as defined in Section 3.2. Furthermore, in order to test the sensitivity of the results to water-land elasticity as well as the imposition of the biophysical relationships, the simulation is run under four different configurations: A. GTAP elasticities without the biophysical constraint of minimum water requirement as defined in Eq. (7), B. GTAP elasticities with biophysical constraint, C. linking-based elasticities without the biophysical constraint, and D. linking-based elasticities with the biophysical constraint. We report the effect of the shock on three main endogenous variables; irrigation quantity demanded, the real GDP, and the real GDP of agriculture. GDP represents the expenditure side. Agriculture includes crops and the livestock sector. The effect of the shock on the price of irrigation capital and the reallocation of factor use is also reported in Table 5. These two are thought of as the main mechanisms that drive the results. Irrigation capital cost and factor demand by each sector are all endogenous variables obtained as part of the model solution.

4 Results and Discussion

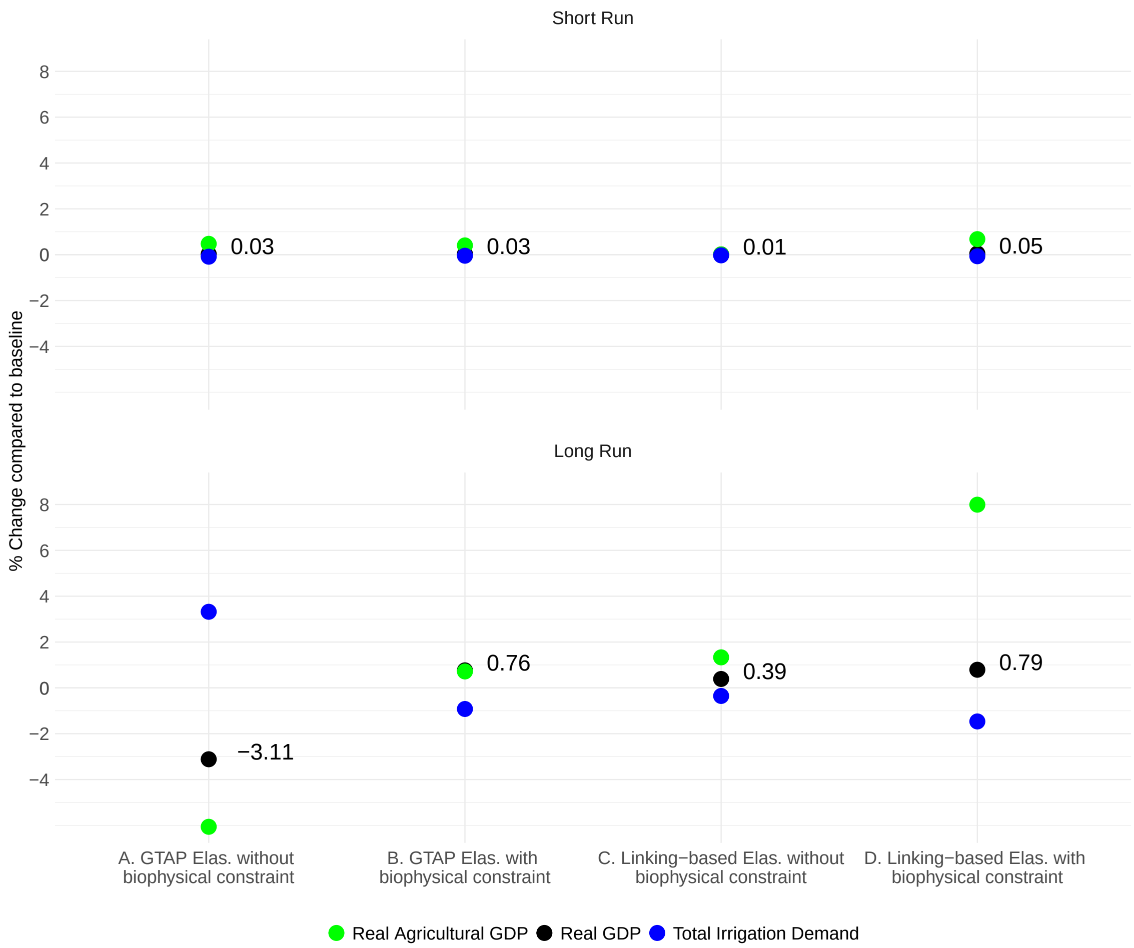
4.1 Short run

In the short run, the effect of the water tax on agriculture and the economy as a whole is essentially negligible across all configurations (Figure 7, upper panel). In particular, in all configurations, irrigation demand did not decrease under the tax shock compared to the baseline. To understand this result, one needs to consider what happens to the (endogenous) price of irrigation capital, the substitute input of irrigation water. The increase in irrigation price causes the price of irrigation capital to increase almost one to

[9] See Section 2.7 on how this price is calibrated

one with the price of irrigation water (Table 5, column 2). This finding is consistent with the result derived in Eq. (3), which shows that what matters is the change in relative prices and not the absolute change. As a consequence, no substantial changes in the variables of interest are observed.

Figure 7: Impact of water tax shock on selected variables under 4 different elasticity configurations in the short and long run. The values represent the percentage change compared to the no-policy scenario. The printed numbers represent real GDP.



4.2 Long run

In the long run, the picture becomes more nuanced. The impacts of the shock on the GDP and the GDP of agriculture are much larger than in the short run and differ by configuration. Overall, the impact on agriculture is positive in all configurations except A (Figure 7, lower panel). Under low elasticity and without biophysical constraint of minimum water requirement (Configuration A), a 50% increase in irrigation price leads to a drop in real agricultural GDP of approximately 6% and GDP declines by 3.1% while irrigation quantity increases. In Table 5, column 3, we see that the factor use (capital and labor) in agriculture drops by 11.4% as a response, which explains this sharp decline in agricultural GDP. All changes are calculated under fixed prices; thus the changes in GDP are real changes (quantity changes). In configuration B, with the same elasticities while imposing the biophysical constraint, both agricultural GDP and total GDP are positively affected by the shock. And this happens while irrigation demand declines by 1.5%. In addition, factor use in agriculture decreases by 3% compared to the no policy scenario.

Table 5: Impact of the water tax shock on selected variables.

	%Δ in price of irrigation capital	%Δ in factor use in Agriculture
	Short run (Long run)	
A. GTAP Elas. without biophysical const.	48.2 (39.1)	0.3 (-11.4)
B. GTAP Elas. with biophysical const.	48.1 (30.2)	0.1 (-3)
C. Linking-based Elas. without biophysical const.	49 (37.5)	0.1 (-1)
D. Linking-based Elas. with biophysical const.	47.5 (33.9)	0.3 (-1.4)

Note: Values represent the percentage change compared to the no-policy scenario. %Δ stands for percentage change. The results for the long run simulations are given in parentheses.

The change in irrigation demand in the long run which occurs in all configurations except A is again consistent with the analysis performed in the method section. Although the increase in irrigation capital cost is still high, the increase is smaller than the reaction in the short run, as shown in Table 5 column 2. This change in the cost of irrigation capital relative to the cost of irrigation water is what causes the decline in irrigation demand.

To interpret these results, it is important to consider that the shock triggers two main channels of input reallocation. The first is the reallocation within agricultural sectors, and the second is the reallocation from agricultural towards non-agricultural sectors.[10] The former affects the agricultural GDP whereas the latter affects the total GDP, with agricultural GDP being a component of total GDP. This indicates improved efficiency in water and factor use in all sectors. In B, agriculture frees more factor resources that go to non-agricultural sectors (3%), resulting in a 0.76% increase in total GDP. This factor reallocation towards more productive sectors occurs under all different configurations except A. Interestingly, configuration A – with low elasticity and no biophysical constraint – is the one most closely aligned with approaches commonly used in the literature, particularly in GTAP-W.

The rise in agricultural GDP alongside the reduction in irrigation demand – in all configurations except A – reflects improved efficiency in irrigation, achieved through employing more irrigation capital, as well as reallocating both irrigation water and irrigation capital within agriculture. This efficiency gain is highest under D, where the calibrated elasticity of substitution and the biophysical constraint are imposed. The effect is weaker when the elasticity is low, as in configuration B, and it is reversed in A. Although one might expect that having less constraints on agricultural production would favor agriculture, the current analysis shows the opposite. Imposing a biophysical constraint in fact fosters a more efficient reallocation of resources within agriculture, ultimately benefiting agriculture as a whole.

Overall, the reason why the policy is more effective in the long run is that more

[10]For a reference on the efficiency gains through reallocation of water, see for instance Hertel and Liu (2019).

adjustments are allowed in factor markets. For comparison, the effect on agriculture in configurations B and D reveals the importance of the elasticity of substitution between land and water input in the long run. Comparison of A with B or C with D underscores the importance of the biophysical constraint.

In sum, low elasticities for the land-water nest might be reasonable for short run analysis. In the long run, however, higher values for the substitution between land and water are warranted if the minimum water requirement is imposed as an additional constraint. Having higher elasticities between water and land in the long run together with the inclusion of the biophysical constraint disciplines the model's response and renders it more capable of capturing realistic reactions and interactions of the economic sectors. Ignoring the biophysical constraint combined with low elasticity is not an adequate way to model production relationships in the economy, and thus the model fails to capture the economic and sectoral impacts of water policy.

4.3 Sensitivity analysis

Beyond the substitution between land and the Fertilizer-Energy-effective-Water composite, another elasticity might be important for the model results, namely the elasticity of substitution between irrigation water and irrigation capital. To assess whether the model results depend on the value of this parameter, we conduct a sensitivity analysis using four different values: 0.5, 1, 2, and 3.

Table 6: Sensitivity test for the policy impact in the long run with calibrated elasticity and biophysical constraint (Configuration D) under different values for the substitution elasticity between irrigation water and irrigation capital.

Elasticity Value	0.5	1	2	3
Real Agricultural GDP	4.7	5.5	8.0	7.5
Real GDP	0.4	0.9	0.8	1.3
Total Irrigation Demand	−1.1	−1.4	−1.5	−1.5

Note: Values for the endogenous variables represent the percentage change compared to the no-policy scenario. Column 4 with an elasticity of 2 is the default value used throughout the analysis. The value for the water intensive crops rice and sugarcane is fixed at 0.1 and 0.2, respectively, where the possibility of substitution between irrigation water and irrigation capital is reasonably low.

We do this using the model specified in configuration D with long run closures. If the effect changes sign, it would indicate that the policy effect is too sensitive to this exogenous parameter. Table 6 shows the impact of the policy (50% increase in irrigation price) on the endogenous variables; real agricultural GDP and total real GDP, as well as total irrigation demand across these four elasticity values. The results show that the effect of the policy changes quantitatively when the elasticity value changes. For example, real agricultural GDP increases by 4.7% under an elasticity of 0.5 compared to the no-policy scenario. If this elasticity is set to 1 instead, column 3, then the agricultural GDP increases by 5.5%, etc. The results show clear non-linearity, since the model itself is highly non-linear. For example, the response of agricultural real GDP is higher at elasticity of 2 than 3, while the total GDP response is the opposite. The total irrigation demand is lower under the policy, as seen in the results section. The reduction becomes slightly stronger for larger values of the substitution elasticity. Importantly, the direction of the effect does not change. The policy impact remains positive regardless of the value of the substitution between irrigation water and irrigation capital. We therefore, conclude that the effect is driven by the policy and is not due to the substitution elasticity between irrigation water and irrigation capital.

5 Conclusion

Irrigation policies in water scarce regions where agriculture is mostly irrigated have economy-wide impacts. Ignoring biophysical realities would result in non-realistic results. This paper presented a novel approach to calibrate the substitution relationship in agricultural production functions. By imposing the yield-water relationship from the crop model PROMET, we solved for the unknown elasticity between land and water in an extended version of the IFPRI CGE model. The resulting elasticities are much higher than those established in the literature.

Applying this set of elasticities and comparing it to those of the GTAP-W model using a water tax shock to Egypt's SAM data shows the different results the model provides. The analysis illustrates that, particularly in the long run, the model results depend on the elasticity of substitution between land and the Fertilizer-Energy-effective-Water nest and, more importantly, the inclusion of the minimum water requirement. The positive impact of the policy shock on agriculture is greater under the novel approach than under the GTAP-W elasticities.

These findings suggest that more caution is needed in modeling the substitution possibility between water and land in agriculture. It also explains a major channel why CGE models studying water policy often provide divergent results. Our work is constrained by data availability issues, particularly for irrigation capital. Furthermore, the magnitude of the results, especially with regard to changes in real GDP, might depend on the size of the agricultural sector in the economy, as well as the water intensity of the sector. Another limitation concerns the values of the elasticities of the other nests. In this regard, however, we took a more conservative approach by applying Leontief functions to main nests, making our results likely to represent a lower bound of the impact of the irrigation pricing policy impact. Finally, the current work assumed that the policy implementation is costless, which might not be realistic given the open access nature of irrigation water, and therefore monitoring costs are likely to emerge. Thus, the gains created by the policy have to be measured against the implementation cost.

This work contributes to the literature on model linking and economic analysis of water policy. The applicability of this method extends beyond Egypt and could be applied to other regions and other applications where (bio)physical realities are considered important input into the analysis.

Appendix A: Water use in agriculture

A representative farmer chooses the quantity of irrigation water to maximize their own net benefits. The choice is twofold. The first level is how much water to use for a given crop.

Second, if there is a water-saving technology, then the farmer also has to decide how much to use of this technology. Having open access to irrigation water w^{ir}, the first level of the farmer's problem is:

$$\max_{w^{ir},\mathbf{x}} \ \pi \ = \ p\ Y(w^{ir},\mathbf{x}) - c^{w} w^{ir} - C(\mathbf{x}) \tag{A1}$$

where p is the unit price of the crop output, Y is output, c^{w} is the unit cost of water delivery (this does not include the value of the water resource), w^{ir} is the water withdrawn to irrigate that crop, Y is strictly concave, and $\mathbf{x}$ is a vector of all other inputs in crop production. Optimality requires that for each factor the value of the marginal product be equal to the marginal cost of that factor, and in particular:

$$\text{FOC:} \qquad p\,\frac{\partial Y(w^{ir},\mathbf{x})}{\partial w^{ir}} \ = \ c^{w} \tag{A2}$$

This is a representation of optimal water use where for each crop produced the representative water user uses water to the level where the marginal value of water in crop i equals the marginal cost of water delivery. This includes all the costs of delivering the water from the main tributary to the field. Now, let us study this problem from the society's perspective as an owner of the water resource in the absence of well-defined water rights. Assume that a social planner optimizes the use of water in all sectors (or crops) as follows:

$$\Pi = \sum_{i}^{n} p_i Y_i(w_i^{ir},\mathbf{x_i}) - c^{w}\sum_{i}^{n} w_i^{ir} - \sum_{i}^{n} C_i(\mathbf{x_i}) \qquad \text{s.t.} \qquad \sum_{i}^{n} w_i^{ir} \leq \bar{W} \tag{A3}$$

Equation (A3) uses the total water supply $\bar{W}$ as a constraint on the social agent who maximizes the total net benefits from water use. Under the assumption that the constraint is binding (this assumption is pursued throughout this paper), setting up the Lagrangian and solving for the optimal point yields:

$$\begin{gathered}\mathcal{L} = \sum_{i}^{n} p_i Y_i(w_i^{ir},\mathbf{x_i}) - c^{w}\sum_{i}^{n} w_i^{ir} - C(\mathbf{x}) - \lambda\Big(\sum_{i}^{n} w_i^{ir} - \bar{W}\Big) \\ \text{FOC:} \qquad p_i\frac{\partial Y_i}{\partial w_i^{ir}} = \underbrace{c^{w} + \lambda}_{p^{w*}}\end{gathered} \tag{A4}$$

where p^{w*} is the price of low-quality water (irrigation water) which includes the value of the resource. The first insight here is that the optimal water use from the social point of view, Eq. (A4), is less than that of the single user wherever λ is greater than zero. Due to the assumed strict concavity of Y, the marginal product in Eq. (A4) is higher than in Eq. (A2), which implies that the level of water in Eq. (A4) must be lower than that in (A2). This happens if the constraint in Eq. (A3) is binding, meaning that water is scarce. It is not surprising that under water scarcity the optimization must take into account the binding water constraint since water now has an opportunity cost. To reflect this, we separate the cost of water into the cost of water delivery and quality c^w and the cost of water in its raw form or the value of the water resource λ. Both of these are assumed to be variable cost and therefore show up in the marginal cost function. Since the objective of the policy is aligning the social optimum of water use with the single-user (decentralized) optimal choice, we assume that the total water available to the economy is divisible, and there is a way to assign these quantities according to some institutional or market rule. Under these conditions, the representative agricultural agent's problem from Eq. (A1) is updated as follows:

$$\begin{aligned} \max_{w^{ir},\mathbf{x}} \ \pi \ &= p\ Y(w^{ir},\mathbf{x}) - c^w w^{ir} - C(\mathbf{x}) \\ &\text{s.t.} \quad w^{ir} \leq \frac{\bar{W}}{n} \end{aligned} \tag{A5}$$

where the quantity of water assigned to each farmer is equal and is given by the total resource supply divided by n where n could be the number of farmers (water users) or the agricultural land area. For more general applications of this problem, this quantity could be set so as to pursue any objective set by the society. In some cases, it might be preferable to prioritize the water use in specific crop production or other non-agricultural uses. This could be done simply by indexing n. Now, let us proceed with the simple case described above. The farmer (water user) solves:

$$\begin{aligned} \mathcal{L} &= p\ Y(w^{ir},\mathbf{x}) - c^w w^{ir} - C(\mathbf{x}) - \lambda\left(w^{ir} - \frac{\bar{W}}{n}\right) \\ \text{FOC: } \frac{\partial \mathcal{L}}{\partial w^{ir}} &: \ p\frac{\partial Y}{\partial w^{ir}} = \underbrace{c^w + \lambda}_{p^{w*}} \end{aligned} \tag{A6}$$

The insight here is that if the planner allocates water according to Eq. (A5), then the social optimum obtained in (A4) and the single user's optimum in Eq. (A6) are identical. Alternatively, if the planner knows the social value of water λ, she can set the price of water p^w to include this. In this case, the single user's optimum would be identical to the social optimum. This is the main conclusion of this section.

As mentioned above, the current model separates both elements of the water cost c^w and λ. This allows us to track the change in the value of the water resource and isolate it from the cost of quality and delivery. For a discussion of the different components of water costs, see Hellegers and Perry (2006). The above exercise shows the first level of choice, which is how to allocate water among crops. The second level of choice is how the water should be delivered to the plants. That is, should flood irrigation be used or apply water-saving technology to reduce water losses?

Each crop has a specific benchmark water requirement $\underline{\mathrm{w}}$ that results in a certain yield. This value is obtained from the biophysical crop model for each crop and for each yield level as described in Section 2.5. However, an exact delivery of this quantity is only possible if a water-saving technology is applied. It follows that if flood irrigation is used, then effective water w must be greater than $\underline{\mathrm{w}}$. This relationship is depicted as:

$$w = \underline{\mathrm{w}} + h(u, K) \tag{A7}$$

where h is a function that defines the substitution possibility between irrigation capital K and residual water, u – the water applied beyond what is needed. This residual water does not contribute to the yield and does not generate any economic value. However, it can be reduced only if irrigation capital K is used to deliver water. If K is low (e.g., flood irrigation), then water losses are high. Given this setup, the farmer has the choice to reduce this residual water by applying water-saving technology to minimize costs. Mathematically:

$$\min_{u,K} \quad p^w u + rK \qquad \text{s.t} \qquad h = \alpha\Big(\delta u^\rho + (1-\delta)K^\rho\Big)^{\frac{1}{\rho}}, \qquad \rho \neq 0,\ \rho < 1 \tag{A8}$$

Where r is the unit capital cost, α, δ, and ρ are standard CES parameters and denote the shifter, the value share, and the elasticity-exponent parameter, respectively. Solving this standard constrained optimization problem for the optimal choice of u and K and rearranging yields:

$$\frac{u}{K} = \left(\frac{\delta}{1-\delta}\ \frac{r}{p^w}\right)^\sigma, \quad \sigma = \frac{1}{1-\rho} \qquad \text{and} \quad \sigma > 0 \tag{A9}$$

This gives the ratio of water loss to irrigation capital. Taking logs and differentiating, we get:

$$\frac{d\log\left(\frac{u}{K}\right)}{d\log\left(\frac{r}{p^w}\right)} = \sigma \tag{A10}$$

Equation (A10) describes the responsiveness of the relative demand for residual water when relative prices change. In sum, the model presented here defines two levels of choice (which are solved simultaneously) where water use optimization occurs. The first is the allocation of water between different crops. The second level of optimization is how to deliver that water at the farm level. In both of these levels, we observe that an incentive-compatible pricing of water p^w as given by Eq. (A4) is necessary to ensure this. Equation (A6) illustrated that the failure to include the value of water resource λ in the price of water p^w leads to a less efficient allocation among crops (or sectors). Equation (A9) also shows that underpricing of water leads to overuse of water and underuse of water-saving technology.

In the theory of production and under regularity assumptions, the demand for an input declines when its price increases. This result is known as Hotelling's lemma (Varian, 1992; Sydsæter et al., 2008). However, what matters in general equilibrium situations are relative changes. This means that changes in relative input demand occur only if relative prices (costs) change. If both prices, for instance, in Eq. (A9) change by the same amount then nothing would happen.

Appendix B: Derivation of the shadow value of water resource

Since the production throughout this paper is described by a nested CES function, let us take a closer look at λ for the case when Y is of CES form. For convenience, the output price is set to 1. By Kuhn Tucker λ is positive whenever supply is less than or equal to demand, that is, the water resource is scarce, which is the case throughout this paper.[11] The production technology is given by:

$$Y = A\left(\delta (w^{ir})^{\rho} + (1-\delta)\,\mathbf{x}^{\rho}\right)^{\frac{1}{\rho}}, \qquad \rho \neq 0,\ \ \rho < 1$$

Setting up the Lagrangian

$$\mathcal{L} = A\left(\delta (w^{ir})^{\rho} + (1-\delta)\,\mathbf{x}^{\rho}\right)^{\frac{1}{\rho}} - c^{w} w^{ir} - C(\mathbf{x}) - \lambda\left(w^{ir} - \frac{\bar{W}}{n}\right)$$

$$\text{FOC:} \quad \frac{\partial \mathcal{L}}{\partial w^{ir}} = Y^{1-\rho}\ \delta\ (w^{ir})^{\rho-1} - c^{w} - \ \lambda\ = 0$$

Where the productivity shifter A is set to 1 for convenience and without loss of generality. Solving for the shadow price using the constraint with equality yields:

$$\lambda = \delta\ Y^{1-\rho}\left(\frac{n}{\bar{W}}\right)^{1-\rho} - c^{w} = \delta\left(Y\frac{n}{\bar{W}}\right)^{\frac{1}{\sigma}} - c^{w}, \quad \sigma\ =\ \frac{1}{1-\rho}\ >\ 0$$
$$\text{with} \quad \frac{\partial \lambda}{\partial \bar{W}} < 0 \quad , \quad \frac{\partial^2 \lambda}{\partial \bar{W}^2} > 0 \tag{B1}$$

Equation (B1) demonstrates the convexity of λ as a function of $\bar{W}$ keeping Y fixed. However, in general equilibrium, the output Y also changes when $\bar{W}$ changes. On the other hand, it can be shown that if $\bar{W}$ is fixed, then the convexity of λ as a function of output Y depends on the value of elasticity between water and non-water input in production σ.

So, now let us check the curvature of λ as a function of $\bar{W}$ and Y to study a situation in which the total supply of water might change (keeping n fixed). Using Eq. (B1) we write:

$$\lambda(\bar{W}, Y) = c\ Y^{\frac{1}{\sigma}} \bar{W}^{-\frac{1}{\sigma}} - c^{W} \quad \text{where} \quad c\ := \delta n^{\frac{1}{\sigma}},\ \delta > 0, n > 0 \tag{B2}$$

The gradient and the Hessian are:

$$\nabla \lambda = \begin{pmatrix} \frac{\partial \lambda}{\partial \bar{W}} & \frac{\partial \lambda}{\partial Y} \end{pmatrix} = \begin{pmatrix} -\frac{c}{\sigma} Y^{\frac{1}{\sigma}} \bar{W}^{\frac{-1-\sigma}{\sigma}} & \frac{c}{\sigma} Y^{\frac{1-\sigma}{\sigma}} \bar{W}^{-\frac{1}{\sigma}} \end{pmatrix}$$

$$H(\lambda) = \begin{pmatrix} c\ \frac{1+\sigma}{\sigma^2}\ Y^{\frac{1}{\sigma}}\ \bar{W}^{\frac{-1-2\sigma}{\sigma}} & -c\ \frac{1}{\sigma^2}\ Y^{\frac{1-\sigma}{\sigma}}\ \bar{W}^{\frac{-1-\sigma}{\sigma}} \\ -c\ \frac{1}{\sigma^2}\ Y^{\frac{1-\sigma}{\sigma}}\ \bar{W}^{\frac{-1-\sigma}{\sigma}} & c\ \frac{1-\sigma}{\sigma^2}\ Y^{\frac{1-2\sigma}{\sigma}}\ \bar{W}^{-\frac{1}{\sigma}} \end{pmatrix}$$

To decide the convexity of λ one needs to check the diagonals and the determinant of the Hessian matrix $H(\lambda)$. The first diagonal term is positive since σ is assumed to be positive, i.e. w^{ir} and $\mathbf{x}$ are substitutes. However, the second diagonal term is positive only if σ is less than 1. Finally, we have to check the determinant of H.

$$\begin{aligned} det(H) = c^2\ \frac{1-\sigma^2}{\sigma^4}\ Y^{2(\frac{1-\sigma}{\sigma})}\ \bar{W}^{2(\frac{-1-\sigma}{\sigma})} - c^2\ \frac{1}{\sigma^4}\ Y^{2(\frac{1-\sigma}{\sigma})}\ \bar{W}^{2(\frac{-1-\sigma}{\sigma})} \\ = \frac{c^2}{\sigma^4}\ Y^{2(\frac{1-\sigma}{\sigma})}\ \bar{W}^{2(\frac{-1-\sigma}{\sigma})}\left(1-\sigma^2-1\right) \\ = -\frac{c^2}{\sigma^2}\ Y^{2(\frac{1-\sigma}{\sigma})}\ \bar{W}^{2(\frac{-1-\sigma}{\sigma})} \end{aligned} \tag{B3}$$

[11] In general, we can write the shadow price of water as $\lambda = f(n/\bar{W}, Y)$. In the simplest case with just one input and logarithmic functional form $Y_i(w_i^{ir}) = \log w_i$, then $\lambda = \frac{1}{w_i^{ir}}$. Substituting this into the constraint yields: $\lambda = n/\bar{W}$.

From this calculation, it is clear that the determinant is negative regardless of σ. Thus, we conclude that the Hessian matrix is indefinite. This implies that nothing can be said about the global curvature of this function.

In Section 3.1 we test this in the data to see how the value of water resource changes when we exogenously change the total water resource. It turns out that the same relationship is observed in the SAM data for Egypt. This means that the value of the water resource changes at an increasing or decreasing rate. The economic interpretation of this result is that the rate at which water prices increase - whether accelerating or decelerating - is determined by the complex intersectoral interactions within the economy. In fact, there are two main effects. First, the decline in water supply raises the water price. The second effect is that the decline in water supply depresses the total output, which in turn reduces the demand for water, and therefore the water price declines. The general equilibrium effect is the sum of all these interactions.

Appendix C: GTAP-W elasticities

Calzadilla et al. (2011) derive the CES elasticity of substitution between irrigation water and land (or the bundle of all other inputs) X when the price of water changes from t to $t(1+\delta)$, which implies that the percentage change is $\Delta t/t = \delta$.[12] By evaluating the water demand at these two different prices and employing the price elasticity of demand $\eta = d \log W / d \log t$ from Rosegrant et al. (2002), they arrive at the following expression for ρ:

$$\rho = -\frac{\ln(1+\delta)}{\ln(1+\eta\delta)} - 1 \tag{C1}$$

Where substitution elasticity, $\sigma = 1/1+\rho$, measures changes in relative factor demand with respect to (the inverse of) relative factor prices:

$$\sigma = \frac{d\ log\left(\frac{W}{X}\right)}{d\ log\left(\frac{p}{t}\right)} \tag{C2}$$

Equivalently, we can write:

$$-\sigma = \frac{d\ log\left(\frac{W}{X}\right)}{d\ log\left(\frac{t}{p}\right)} \tag{C3}$$

where p denotes the price of the input bundle X. Two things can be observed here. First, the difference between η and $-\sigma$ can be written as

$$D = -\sigma - \eta = \eta\left(\frac{1}{\epsilon} - 1\right), \quad \text{where} \quad \epsilon = \frac{d\ log\ X}{d\ log\ p} < 0 \tag{C4}$$

Proof:

$$\begin{aligned} D &= \frac{\Delta W/W}{\Delta t/t}\,\frac{\Delta p/p}{\Delta X/X} - \frac{\Delta W/W}{\Delta t/t} \\ &= \frac{\Delta W/W}{\Delta t/t}\left(\frac{1}{\frac{\Delta X/X}{\Delta p/p}} - 1\right) = \eta\left(\frac{1}{\epsilon} - 1\right) \end{aligned} \tag{C5}$$

[12] This is the notation used in Calzadilla et al. (2011)

Where ϵ is the demand elasticity of the other factor with respect to its own price. In general equilibrium models, changing the price of one factor affects the prices of the other factors. Even if one would fix p, it is clear from Eq. (C1) that the substitution elasticity between water and non-water inputs is not constant as introduced and used in the GTAP-W model. The value of elasticity in GTAP-W for North Africa, for example, is 0.08 at η equal to -0.07 as reported in Calzadilla et al. (2011, p. 22) for that region. This value for σ corresponds to a specific percentage change in the price of irrigation water δ that happens to be an increase of 50% compared to the baseline according to our calculation using (C1) . In the following, we show that $d\rho/d\delta < 0$ or equivalently $d\sigma/d\delta > 0$. In other words, the substitution elasticity increases as the price of water increases further. In the following lines, we prove this result. Differentiating Eq. (C1) we get:

$$\frac{d\rho}{d\delta} = \frac{-\frac{\ln(1-\eta\delta)}{1+\delta} + \frac{\eta\ln(1+\delta)}{1+\eta\delta}}{\left[\ln(1+\eta\delta)\right]^2} \tag{C6}$$

Since the denominator is a positive term, we need only to check the sign of the numerator. Define:

$$\phi := \frac{-\ln(1+\eta\delta)}{1+\delta} + \frac{\eta\ln(1+\delta)}{1+\eta\delta} \tag{C7}$$

Using Taylor expansion $T(\delta)$ around point zero for small changes in δ:

$$\begin{aligned} \ln(1+\eta\delta) &\approx \eta\delta - \frac{\eta^2\delta^2}{2} \\ \ln(1+\delta) &\approx \delta - \frac{\delta^2}{2} \end{aligned} \tag{C8}$$

Inserting this into (C7) and ignoring the small values we obtain:

$$\phi \approx \frac{-\eta\delta}{1+\delta} + \frac{\eta\delta}{1+\eta\delta} = \eta\delta\left(\frac{1}{1+\eta\delta} - \frac{1}{1+\delta}\right) < 0 \tag{C9}$$

The first term inside the bracket is larger than the second term since η is negative, which makes the whole expression inside the bracket positive. Since η is negative, ϕ is negative. The claim is proven.

Appendix D: Irrigation capital

Because data on irrigation capital is available only at an aggregated level, we proceed by making two assumptions. First, it is assumed that advanced irrigation technologies are applied exclusively in the so-called *new Lands*. This land has been reclaimed in recent decades and lies beyond the Nile valley and Delta, which is also called the *old Lands*.[13] In old Lands, flood irrigation has historically been the norm (Gersfelt, 2007).

[13]Old Lands refer to the Nile Valley and Delta, and New Lands is the land reclaimed since the construction of the High Aswan Dam (1970), which enabled this reclamation, generally less fertile, on the old Lands' fringes, as well as new locations outside the Nile Valley and Delta such as western desert (FAO, 2016), also see Figure E2

The FAO data report (FAO, 2016) documents that 20% of the area in 2010 is irrigated using advanced technologies (drip irrigation and sprinkler irrigation). This requires us to know the share of new Lands in the total area. This data is provided by the Ministry of Agriculture (Annual Statistics, 2019). Using this, we create a new SAM account for irrigation capital.

The following numerical example illustrates the method used to construct the share of irrigation capital by crop. Suppose that there are two crops grown on both types of land, with areas reported in Table D1 and that all we know about the use of advanced irrigation technology is that 20% of the total area is equipped with this technology. We note that crop 2 is cultivated more on new Lands than crop 1. Second, we impose a proportionality assumption, i.e., it is required that the proportion of advanced technology used in each crop is equal to the ratio of new Lands to old Lands of that crop. Implementing this in the current example gives:

$$\text{ratio of new Lands to old Lands}_{12} = \frac{0.2}{0.4} = 0.5$$

Table D1: A hypothetical example – the area cultivated with each crop

	Crop 1	Crop 2	Total
Old Lands	8	6	14
New Lands	2	4	6
Total	10	10	20

This means that the ratio of applied technologies between crop 1 and crop 2 must also be 0.5 (the proportionality assumption). If the area equipped with the technology of crop 1 and crop 2 is x_1 and x_2, respectively, then we have a system of two linear equations:

$$x_1 - 0.5x_2 = 0$$
$$x_1 + x_2 = 4$$

where 4 is the total area equipped with the technology (20% of the total area). Solving this gives the unique solution:

$$x_1^* = \frac{4}{3} \text{ and } x_2^* = \frac{8}{3}$$

That is, 1.33 units of land used for crop 1 out of 10 units are equipped with irrigation technology, while 2.67 units used for crop 2 are equipped with irrigation technology, and in total 4 units of land out of 20 are equipped with irrigation technology.

Generalizing this to n crops, letting a_i denote the share of crop i in new Lands with $\sum_i^n a_i = 1$ we can write:

$$\begin{aligned} x_1 &= a_1 x \\ x_2 &= a_2 x \\ &\vdots \\ x_{n-1} &= a_{n-1} x \\ x_1 + \ldots + x_{n-1} + x_n &= x \end{aligned}$$

where x_i is the area cultivated with crop i and equipped with irrigation technology, and x is the total area equipped with irrigation technology. This is a system of equal number of equations and unknowns. Since a_i for all i and x are known from the data, the unique solution for this linear system is the vector $c^* = (x_1^*, x_2^*, ..., x_n^*)$.

Appendix E: Figures and tables

Figure E1: Nested production function for non-agriculture in the extended model

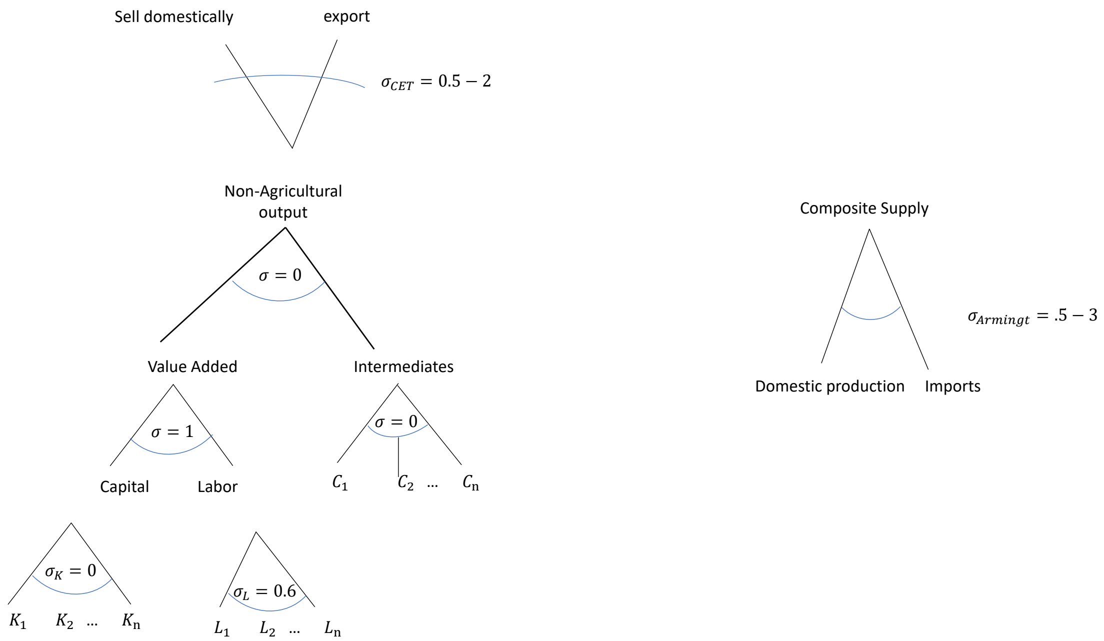
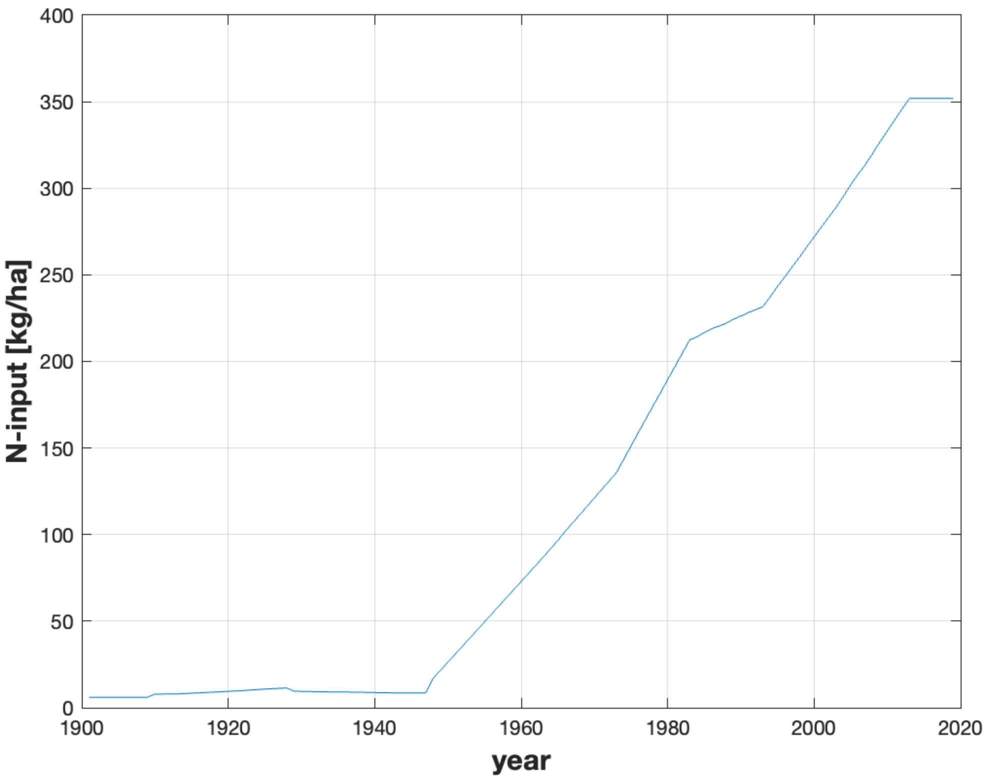


Figure E2: Egypt's irrigation map

Source: Ministry of Irrigation and Water Resources

Figure E3: Historical nitrogen inputs as a sum for nitrogen fertilizer, manure application, and atmospheric nitrogen deposition from 1901 to 2019 (Volkholz and Ostberg, 2022)



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