7-20-2004

Substitutions between Water and other Agricultural Inputs - A Modeling Analysis

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This is the abstract of a presentation given on Tuesday, 20 July 2004, in session 2 of the UCOWR conference.

Substitutions between Water and other Agricultural Inputs – A Modeling Analysis

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Abstract

Increasing concerns about water availability, water quality, ecosystem sustainability, and food security have led to an increased importance of quantitative assessments of the substitution between water and other agricultural inputs at the margin for agricultural and environmental policy analysis. This paper explores the potential substitutions between water and other agricultural inputs through an integrated hydrologic-economic modeling framework. Compared to the multi-input multi-output production framework, the modeling framework used here represents essential hydrologic and environmental relations determining both water supply and demand endogenously, which allows a more detailed substitution analysis between water and other inputs. The model is applied to the Maipo River Basin in Chile. It shows that a tradeoff between additional water use of 301 million m^3 and additional net profits of USD 11.0 million in the basin. Moreover, under an increase in water prices by a factor of 8, a reduction of water withdrawals by 326 million m^3 is traded off with costs of USD 43.2 million for other inputs, particularly seed and labor inputs, which will assure that profit is maintained at the baseline level.

Key Words: Water management, irrigation, substitution, agricultural inputs, optimization

Introduction

Increasing concerns about water availability, water quality, ecosystem sustainability, and food security have led to an increased importance of quantitative assessments of the substitution between water and other agricultural inputs at the margin for agricultural and environmental policy analysis. Plant growth is limited to the level afforded by the input, which is most constrained or least available. Substitution among inputs does not necessarily lead to higher yield but it can change the demand of different resources. Different levels of water application can alter the non-limiting levels of other inputs, particularly mobile plant nutrients. Such substitutions at the intensive margin can reduce the environmental cost of producing agricultural products or the cost of joint agricultural and environmental outcomes. Edwards et al. (1996) show that farmers respond to increases in electricity cost by substituting between water and other inputs, by changing the crop allocation on irrigated land, and by changing the total irrigated area.

Quantitative substitution assessments are usually conducted through production functions, which present the technological relationships that determine the maximum quantities of agricultural outputs that can be produced from given combinations of inputs (Heady and Dillon 1961). Fernandez-Cornejo (1992) provides a procedure for assessing short and long-run demand and substitution of agricultural inputs, based on the estimation of a theoretically consistent restricted profit function and using a series of decomposition equations. Howitt and Msangi (2002) present a multi-input multi-output production framework, within which the potential for substitution can be explicitly modeled. The framework is used as a basic policy tool, with incentives or penalties leading to input substitution under given agricultural technology.

This paper explores the potential substitutions between water and other agricultural inputs within an integrated economic-hydrologic modeling framework. Compared to the multi-input multi-output production framework, the modeling framework used here represents essential hydrologic and environmental relations determining both water supply and demand endogenously based on hydrologic, economic, and institutional relations. This allows a more detailed substitution analysis between water and other inputs. The rest of this paper will first introduce the model and the case study area, presents a baseline modeling solution calibrated to the inputs and outputs of the base level, then discusses alternative scenarios on substitutions between water and other inputs, and finally provides a conclusion.

Model and Case Study Area

Cai et al. (2003) presented a model for optimal allocation and use of water resources that incorporates hydrologic, economic, agronomic, and institutional relationships essential in the context of river basins. The river basin modeling system is developed as a node-link network, with nodes representing physical entities and links the connection between these entities. The nodes included in the network are source nodes, such as rivers, reservoirs, and groundwater aquifers and irrigation and municipal and industrial (M&I) demand nodes, which are connected to the basin network. Agricultural demand sites are delineated according to the irrigation districts. At each agricultural demand site, water is allocated to a series of crops, according to their water requirements and economic profitability. In addition to these off-stream uses, instream uses are considered, including minimum flows for environmental uses, flows for waste (salt) dilution, and for hydropower generation. Based on the node-link network, an economic optimization model has been developed with the objective to maximize economic returns to water uses at the basin level.

The key component of the model making it appropriate for the substitution analysis is the crop yield function, which has water and other inputs as variables, such as irrigation investment, fertilizers, pesticides, machinery, labor, and seeds. The crop yield function used for the case study area will be described in detail. Such a modeling framework might have the following advantages: realistic water accounting, based on spatially and temporally distributed water demand and supply; endogenous determination of water demands; endogenous consideration of institutions and policy constraints; and empirical estimation of economic returns to water use. These can be achieved because the water balance and water quality (here salinity levels in irrigation runoff) are simulated in the basin network, and costs and benefits for all demand sites are considered within a consistent model based on the supply-demand network.

The model is a short-term static model in terms of economic processes, whereas the hydrologic component simulates storage operations and water balance over 12 time intervals (months) within a one-year period. Thus, no explicit inter-temporal discounting of costs and benefits can be incorporated. The model can only be used to examine the economic and environmental consequences within a short-term framework or for a representative year characterized with technological and policy specifications. The examination of the substitutions between water and other agricultural inputs even at the level of a representative year can yield important policy conclusions, as shown in this paper through the application of the model to a case study area, the Maipo River Basin in Chile.

The Maipo River Basin, located in a key agricultural region in the metropolitan area of central Chile has experienced growing water shortages and increasing competition for scarce water resources across sectors. The basin is characterized by a very dynamic agricultural sector—serving an irrigated area of about 127,000 ha (1270 km^2 out of a total catchment area of 15,380 km^2)—and a rapidly growing industrial and urban sector, particularly in the capital city of Santiago with a population of more than 5 million people. More than 90 percent of the irrigated area in the basin depends on water withdrawals from surface flows. In the mid-1990s, total water withdrawals at the off-take level in the Maipo River Basin were estimated at 2,144 million m^3, about 48 percent of the annual average flow in the basin (4,445 million m^3). During the low-flow season, irrigation is of particular importance for perennial crops, like fruit trees and grapes. Agricultural demand sites are delineated according to irrigation districts (A1-A8 shown in Figure 1), with irrigated areas ranging from 1,300-45,000 ha. Irrigated areas in the basin have been gradually declining due to increasing demands by the domestic and industrial sectors for both water and land resources, among other factors. However, the closeness to the capital city also provides a profitable outlet for high-value crop production both for the local market and for the dynamic export sector. Currently, agriculture accounts for 64 percent of total withdrawals.

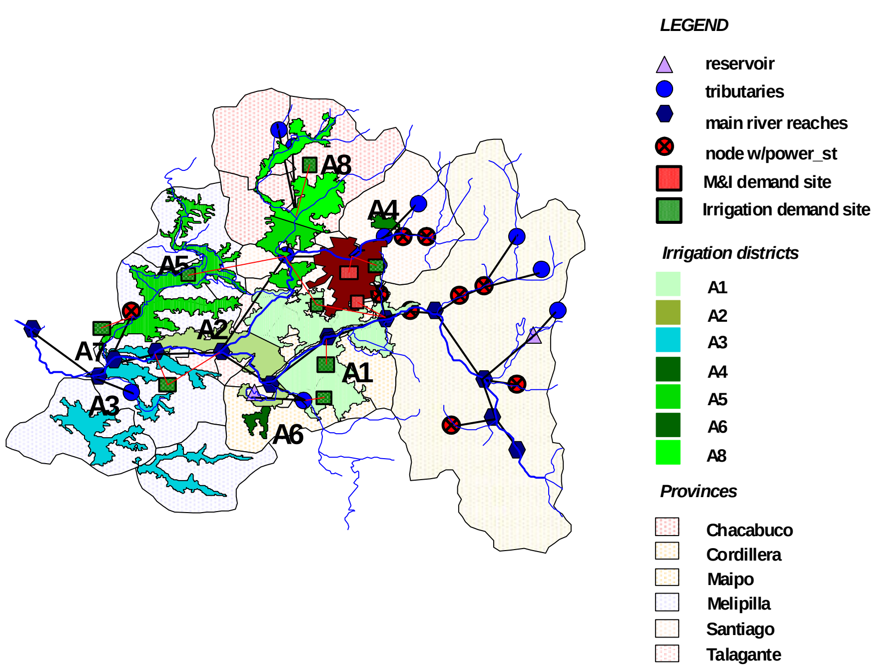

Figure 1: The Maipo River Basin, Chile including irrigation demand sites (A1-A8)

Crop Yield Specification

The crop yield function has been developed based on econometric analysis from an agricultural production survey carried out in the Maipo River Basin. Crop yield has been estimated as a function of several agricultural inputs, including irrigation investment, application of fertilizer, pesticides, machinery, labor, and water. In order to establish a relationship between agricultural inputs and crop yield, a quadratic production function is chosen due to its properties of decreasing marginal returns to additional inputs and substitutability of inputs. The quadratic function is expressed as follows:

$$y(x_1, x_2, ..xi) = [\alpha_1, \alpha_2, \alpha_3, \alpha_n,] \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_i \end{bmatrix} - \begin{bmatrix} x_1 & x_2 & x_3 & x_n \end{bmatrix} \begin{bmatrix} \gamma_{11} & \gamma_{12} & \gamma_{13} & \gamma_{1m} \\ \gamma_{21} & \gamma_{22} & \gamma_{23} & \gamma_{2m} \\ \gamma_{31} & \gamma_{32} & \gamma_{33} & \gamma_{3m} \\ \gamma_{n1} & \gamma_{n2} & \gamma_{n3} & \gamma_{nm} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_i \end{bmatrix} \tag{1}$$

where $\boldsymbol{x_i}$ represents crop inputs, α is the vector of linear coefficients, and γ is the vector of cross-item coefficients.

The crop production survey was carried out during the months of August to October of 1999 by the Catholic University of Chile for a total of 300 households in the Metropolitan Region as well as in Regions V and VI, located within the Maipo River Basin. Due to the limited number of samples available from the survey and the unreliable quality of the samples, conventional econometric estimates would be restricted by the ill-posed or ill-conditioned data sets. As a result, the quadratic yield function shown in Equation 1 was estimated using the Generalized Maximum Entropy (GME) approach (Golan et al., 1996, Mittelhammer et al., 2000). GME combines incomplete information and plausible assumptions and derives new information, which is normally not accessible from traditional analytical approaches. GME was used for regression analysis with incomplete samples first by Golan et al. (1996). The program that calculates the yield functions applied for this study was originally developed by Richard Howitt of University of California at Davis, USA, and Arnaud Reynaud of INRA (Institute National de la Recherche Agronomique) in France. This approach enables the estimation of flexible form yield function parameters for the case of limited small sample information. The model uses first-order conditions derived from the desired model structure and a yield function as estimating equations. Major assumptions relate to the range of the marginal costs of the inputs (ratio of input cost to crop price). Details of the GME program should be referred to Howitt and Msangi (2002).

Based on the quadratic crop yield function, the net profit from irrigation from a demand site can be expressed as:

$$
\begin{aligned}
VA(dm) = & \sum_{cp} A(dm,cp)\, Y_a(dm,cp)\ \ p(dm,cp) - \\
& \sum_{ki}\sum_{cp} A(dm,cp)\cdot inp(dm,cp,k)\cdot cinp(dm,cp,k)
\end{aligned}
\qquad (2)
$$

where k is used as an index for agricultural inputs, *inp* is the input of water, irrigation investment, fertilizer, pesticide, labor, machinery, and seed per hectare, and *cinp* represents the input costs. The objective of the model is to maximize the net irrigation profit over all demand sites.

Modeling Scenarios for Substitution Analysis

Baseline Scenario

The baseline scenario (BAS) represents a set of "normal" inputs and corresponding "normal" outputs. The normal inputs include average water inputs and other inputs, as shown in Table 1, as well as normal weather, current level of technology and management, and regular system operations (e.g., reservoir operations). The normal outputs include 1) flow through river reaches; 2) water withdrawals to both agricultural demand sites and municipal and industrial sites, if they are observable; 3) crop harvested area and yield; and 4) farmer incomes. These normal inputs and outputs are assessed based on a farm survey conducted in the case study area. Given the "normal" inputs, the model outputs are calibrated to the estimated "normal" outputs through an integrated calibration program (Cai, 2004). Annual water withdrawals to demand sites, average crop yields, and crop areas by crop and by demand site are shown in Tables 2-4, respectively. The baseline scenario then provides a start point for alternative scenario analysis on the substitution between water and other inputs as discussed in the following.

Table 1: Agricultural inputs and net profit, total values and values per unit of crop area under the baseline scenario (BAS)

		A1	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**Basin**
Water	*(106 m3)*	664	244	382	15	476	47	17	168	2013
	(m3/ha)	15,415	15,298	16,351	14,190	15,869	15,201	15,782	14,486	15,580
Irri. Invest.	*(106 $)*	12.1	4.3	5.1	0.3	6.9	0.9	0.2	3.5	33.2
	($/ha)	280	272	217	241	230	275	150	305	257
Fertilizer	*(106 $)*	7.4	2.7	3.7	0.2	4.8	0.5	0.1	1.7	21.1
	($/ha)	172	167	157	169	159	168	129	149	163
Pesticide	*(106 $)*	5.2	2	2.3	0.1	3.1	0.4	0.1	1.4	14.6
	($/ha)	122	124	100	107	103	124	72	121	113
Seed	*(106 $)*	6.9	2.4	3.3	0.2	4.3	0.5	0.1	1.5	19.3
	($/ha)	161	153	140	182	144	156	120	131	149
Labor	*(106 $)*	38.1	14.6	14.7	0.7	19.7	2.9	0.4	10.3	101.4
	($/ha)	884	917	629	679	658	931	335	885	785
Machinery	*(106 $)*	15.9	6	8.8	0.3	11	1.2	0.3	4.5	48.1
	($/ha)	370	379	378	327	368	378	265	383	372
Net Profit	*(106 $)*	34.9	13.1	13	0.6	17.9	2.6	0.3	10.5	93.0
	($/ha)	810	822	555	622	598	830	282	905	720

Table 2: Average crop yields (metric ton per ha)

Crops	Annual Forage	Avocado	Carrot	Corn	Grape	Lemon	Onion
Yield	13.0	8.4	23.4	9.1	17.0	26.8	25.5
Crop	Peas	Peach	Potato	Prairie	Pumpkin	Wheat	Others
Yield	5.7	18.2	41.1	14.0	27.1	4.8	13.0

Table 3: Annual water withdrawal (million m^3)

Demand site	A1	A2	A3	A4	A5	A6	A7	A8	M&I	Basin
withdrawal	782.3	310.3	451.5	17.3	575.1	56.8	16.5	225.2	744.4	3179.3

Table 4: Irrigated area in hectares, actual data

Crop	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**Basin**
Wheat	6,834	2,515	3,712	225	4,964	504	322	2,971	22,046
Corn	6,994	2,624	3,479	205	4,283	530	13	88	18,215
Annfor	4,214	1,560	3,208	127	4,202	283	384	801	14,780
Grape	6,176	2,532	709	35	1,277	502	1	1,708	12,941
Peach	4,308	1,685	934	94	1,716	330	1	1,564	10,631
Potato	3,150	1,115	1,031	39	1,253	225	17	525	7,354
Pumpkin	1,548	542	792	83	1,217	107	25	364	4,675
Lemon	1,759	675	1,161	35	1,333	134	2	309	5,405
Avocad	1,010	383	590	15	709	74	4	206	2,991
Onion	1,282	503	590	16	687	100	19	154	3,350
Carrot	1,165	377	517	39	747	74	16	403	3,339
Peas	1,473	308	549	32	810	60	18	953	4,201
Prairie	433	194	4,169	5	4,254	15	131	60	9,261
Other	1,954	710	1,516	76	2,106	132	114	1,314	7,924
TOTAL	42,300	15,722	22,958	1,025	29,555	3,069	1,063	11,420	127,111

Alternative Scenarios

Alternative modeling scenarios are defined based on the baseline scenario (BAS). The alternative scenarios explore the substitution effects among water and all other inputs, each of which is allowed to change within a prescribed range. The following two scenarios are defined:

- Full optimization scenario for substitution analysis (FOPS), starting from BAS and allowing for water and other inputs to change within prescribed ranges (0.5-2.0 times BAS values).
- Substitution among water and other inputs (SUB) keeping net profits close to BAS. This scenario is the same as FOPS, allowing water and other inputs to change within prescribed ranges but water prices are increased to decrease water application. The

scenario is implemented through increasing water prices gradually up to the point where the total net profits are close enough to the BAS.

Table 5 presents the results for agricultural inputs and net profits (total values and values per ha) for FOPS and BAS in percentage terms; Table 6 presents these results for SUB and BAS. Under FOPS, almost all inputs increase for all irrigation districts compared to the BAS scenario. Thus, increasing water and other inputs, within prescribed ranges, are the preferred strategy under profit maximization. Larger increases of water application will occur in some downstream irrigation districts, like A3, A5, and A7, and smaller increases in some upstream irrigation districts, like A1 and A8, where water is relatively less constrained. In percentage terms, the increase in pesticide usage is lowest, followed by water. Compared to the BAS scenario, total water application increases by 301 million m^3, the total cost for other inputs increases by USD 66.6 million, and net benefits increase by USD 11.0 million.

Table 5: Differences of agricultural inputs and net profits (total values and values per ha) between FOPS and BAS in percentage (%)

		A1	A2	A3	A4	A5	A6	A7	A8	Basin
Water	Total	11.7	15.6	17.8	20.0	18.7	14.9	23.5	8.3	15.0
	Per ha	2.2	2.3	4.0	4.4	5.2	2.6	6.2	0.8	3.3
Irri. Invest.	Total	16.5	23.3	21.6	0.0	18.8	11.1	0.0	14.3	18.7
	Per ha	7.1	8.1	8.3	2.1	5.7	8.0	-4.7	4.6	6.6
Fertilizer	Total	32.4	29.6	27.0	0.0	25.0	40.0	97.2	29.4	29.4
	Per ha	21.5	17.4	12.1	20.7	11.9	18.5	-0.8	16.8	16.6
Pesticide	Total	15.4	15.0	13.0	0.0	9.7	0.0	0.0	14.3	13.7
	Per ha	4.9	2.4	-2.0	2.8	-1.9	4.0	-18.1	6.6	2.7
Seed	Total	46.4	50.0	39.4	50.0	41.9	40.0	99.2	40.0	43.0
	Per ha	32.9	30.7	24.3	30.8	25.0	30.8	12.5	28.2	28.9
Labor	Total	34.1	37.0	25.2	28.6	27.9	34.5	0.0	35.0	32.0
	Per ha	22.9	21.0	10.3	10.8	12.9	20.9	4.2	26.0	18.5
Machinery	Total	20.1	23.3	29.5	33.3	28.2	16.7	33.3	20.0	23.9
	Per ha	9.5	7.9	14.0	9.5	13.3	7.4	23.0	13.1	11.6
Net Profit	Total	9.7	13.7	14.6	33.3	14.0	11.5	33.3	8.6	11.8
	Per ha	0.5	0.9	1.6	5.5	1.0	-0.1	1.4	1.1	0.4
Total Cost*	Total	28.7	31.6	26.4	22.2	26.5	26.6	25.0	27.5	28.0

While FOPS does not show any potential for substitution between water and other agricultural inputs (inputs are complementary), Table 6 shows substitution effects when water prices change. Allowing water and other inputs change over ranges around the current levels, about 8 times of the current water prices for irrigation will enforce the substitutions shows in Table 6, while net profits are maintained. In the basin scope, higher substitutions of water are found with seed (reflecting agricultural research) and labor; lower substitutions are found with pesticides and machinery, respectively. A reduction of water application by 326 million m^3 leads to cost increases by other inputs of USD 43.2 million.

Table 6: Differences of agricultural inputs and net profits (total values and values per ha) between FOPS and BAS in percentage (%)

		A1	A2	A3	A4	A5	A6	A7	A8	Basin
Water	Total	-13.3	-7.0	-26.4	-6.7	-20.6	-8.5	0.0	-10.1	-16.2
	Per ha	-12.3	-8.9	-24.0	-7.0	-18.9	-10.3	-7.5	-8.8	-15.2
Irri. Invest.	Total	12.4	18.6	11.8	0.0	11.6	11.1	0.0	11.4	13.1
	Per ha	14.3	15.4	17.1	8.3	13.9	15.6	-2.0	11.8	14.4
Fertilizer	Total	16.2	14.8	8.1	0.0	8.3	20.0	0.0	17.6	12.5
	Per ha	16.9	13.8	12.1	14.8	10.7	14.9	-2.3	15.4	14.1
Pesticide	Total	5.8	5.0	0.0	0.0	0.0	0.0	0.0	7.1	3.5
	Per ha	6.6	4.0	2.0	2.8	1.9	4.8	-18.1	9.1	4.8
Seed	Total	30.4	33.3	24.2	50.0	27.9	20.0	100.0	26.7	28.1
	Per ha	31.1	28.8	30.0	29.7	29.2	28.8	15.0	27.5	30.0
Labor	Total	28.3	30.8	14.3	28.6	18.3	31.0	0.0	30.1	24.7
	Per ha	30.0	27.9	18.1	16.6	20.5	28.2	4.5	32.0	26.2
Machinery	Total	11.3	15.0	8.0	33.3	9.1	8.3	33.3	13.3	10.7
	Per ha	12.4	11.1	11.1	12.5	11.4	10.8	17.0	15.9	12.2
Net Profit	Total	-0.9	3.1	0.0	16.7	0.6	0.0	0.0	-1.9	-0.1
	Per ha	0.2	0.9	3.4	4.7	2.3	-0.4	-7.8	-0.2	1.1
Total Cost*	Total	20.7	23.4	11.9	22.2	14.1	20.3	16.7	21.4	18.2

Conclusions

Based on a quadratic crop yield function with multiple agricultural inputs, this paper presents substitution effects between water and irrigation investment, fertilizer, pesticides, labor, machinery, and seed. The analysis is derived directly from the crop yield function and also from scenarios of a "positive mathematical model". The model is calibrated to a baseline scenario through the determination of the opportunity cost for water and crop area and a number of other economic and hydrologic parameters.

The shift from a baseline scenario, which is calibrated to actual conditions, to full basin optimization, leads to increasing input use of those inputs that are complementary to water, in particular for seed and labor. However, the environmental value of water is not explicitly taken into account. The tradeoff here is between additional water use of 301 million m^3 and additional net profits of USD 11.0 million; an additional concern is the possible negative impact to the environment from additional use of fertilizers and pesticides. Under economic incentives (represented to an increase in water prices by a factor of 8), a reduction of water withdrawals by 326 million m3 is traded off with costs of USD 43.2 million for other inputs, particularly seed and labor inputs, which will assure that profit can be maintained. Substitutions between water and other crop inputs vary substantially by irrigation district, depending on the relative cropping patterns, net profit per unit area, and net profit per unit of water application.

Acknowledgements

Drs. Richard Howitt and Arnaud Reynaud provided a GME program code for generating the crop yield function; Dr. Guillerm Donoso led the farm survey of the agricultural production data; Dr. Mark Rosegrant was the leader of project that this paper is based on. The authors are grateful for their generous help and research fund from the Inter-American Development Bank and the Consultative Group for International Agricultural Research.

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