ESTIMATING THE EFFECT OF WATER CHARGE INTRODUCTION AT SMALL-SCALE IRRIGATION SCHEMES IN NORTH WEST PROVINCE, SOUTH AFRICA

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Abstract

In South Africa water law has recently changed, adopting the principle of water as an economic good, thus levying charges on its use. For small-scale irrigators this is an important change, because currently their water use is entirely subsidized. In the coming years, subsidies will gradually decrease and an essential expected benefit of this policy change is that water use efficiency will rise, leading to reduced consumption and possible reallocation of the water saved. The exact impact of the water pricing policy on the irrigation water use or on the farmers' production system is however unclear. This study introduces a new methodology, based on data envelopment analysis, that allows estimating the effects on the agricultural production process and water demand of introducing or raising a water price. It is revealed that a large majority of the farmers does not adjust water use. Production costs however were shown to increase significantly.

Key words: water pricing, water savings, irrigation, data envelopment analysis, South Africa

1. Introduction

Irrigation systems are the main consumptive users of water at world level. Due to the growing water scarcity irrigators experience increasing pressure to release water for other uses and to find ways in which to improve performance (Perry, 2007; Malano et al., 2004; Perry, 2001). Efficient use of water resources is therefore considered a fundamental target for farmers and water management (Ortega et al, 2004). In this respect, the apparent misuse and waste of irrigation water, in the context of low and subsidised water prices, call for a more prominent role of market forces in encouraging efficient water use (Liao et al., 2007; Gómez-Limón and Riesgo, 2004; Becker and Lavee, 2002; Perry, 2001).
Increasing the price of irrigation water or simply introducing a price is believed to have two important positive effects. Firstly, it will make consumers aware of the scarcity, creating a new respect for water, which should improve management efficiency and secondly provide incentives to farmers to rethink crop choices, stimulating the shift to more profitable crops (Easter and Liu, 2007; He et al., 2006; Becker and Lavee, 2002; Tardieu and Préfol, 2002; Abu-Zeid, 2001). However, according to Tardieu and Prefol (2002) and Liao et al. (2007) rises in water prices are not without risk. They could lead to an overall reduction in a country's agricultural production, endangering the goal of securing food self –sufficiency. They could lead to higher prices for urban consumers resulting in increased import and loss of market share for local irrigating farmers. Finally they could lower agricultural income with negative effect on rural development. In addition, Abu-Zeid (2001) adds that increasing or introducing water charges in many parts of the world is a sensitive issue involving historical, social and even religious dimensions and that the effect of irrigation rates on efficiency might be insignificant if they represent too small a proportion of the total production costs. Yet another reason reported to expect only limited effects is the low elasticity of demand for irrigation water (Gómez-Limón and Riesgo, 2004; Berbel and Gómez-Limón, 2000).

Taking into consideration the possible disadvantages and the limited effect it might have on water saving, it is clear that there is an urgent need for methodologies that allow to estimate as accurately as possible, the effects on the agricultural production process and water demand of introducing or raising a water price (Ortega et al, 2004). Several authors (Gómez-Limón and Riesgo, 2004; Berbel and Gómez-Limón, 2000; Gómez-Limón and Berbel, 2000) have used linear programming models to determine water demand functions. For different levels of water price, these models predict changes in cropping activities and linked to this, changes in water use based on one or more objective functions. These models require however a list of possible cropping alternatives with the levels of input and output for each alternative determined a priori. As a consequence shifts between different inputs in one alternative are not captured in a dynamic way by this kind of models.

Hence a new methodology that is able to estimate shifts in input use is proposed in this study. It consists a novel two-stage application of Data Envelopment Analysis (DEA). In the first step a common DEA is used to calculate the technical and allocative efficiency of the farmers under the current conditions. In the second step these values of technical and allocative efficiency are used as characteristics of the farming operations on each farm. This allows estimating the adjustments farmers will make in their input vectors in response to the introduction of the water charges. The comparison of the simulated level of water use with the current one offers an interesting insight in the water saving effect of the introduction of water charges.

To analyse the effect on water use and on the production system of the introduction of a water price, this study uses data of a sample of 60 small-scale irrigators in North West Province, South Africa. Although the sample is relatively small, this case study reflects the typical situation of many rural areas in South Africa and thus provides interesting insights. Moreover the sample suffices to demonstrate the possibilities of the methodology adopted. In South Africa the recently changed water law adopts the principle of water as an economic good, thus levying charges on its use. For farmers at small-scale irrigation schemes this is a new challenge, because currently their water use is entirely subsidized. The subsidies will gradually decrease and farmers will have to pay to ensure cost recovery (DWAF, 2004). As in most cases one of the expected benefits of this policy change is that water use efficiency will rise. The exact impact of this change on the irrigation water use or on the farmers' production system is however unclear. Yet this is important because these small-scale irrigation schemes provide a livelihood for many rural households. Apart from employment opportunities, these schemes are believed to play a role in rural development by their potential to alleviate food insecurity and to generate additional income opportunities (Perret and Touchain, 2002; Perret, 2002).

From here on the paper is organised as follows. The second section will provide the methodology, starting with a short introduction on the measurement of efficiency using DEA. The section continues with the introduction of the model for simulating the effect of water pricing on water use and ends by describing data collection. Next, the methodology is first applied on a simple numerical example with graphical representation and then on the dataset from South Africa. Results of the different steps are presented and discussed. The final section concludes by summarizing the main points and suggesting policy implications.

2. Methodology

2.1. Measuring efficiency

The first step in this study consists of determining the current efficiency levels of the farms in the sample. Efficiency here refers to the global relationship between all outputs and inputs in the production process (Rodríguez Díaz et al., 2004b). Efficiency performance of a farm can be evaluated based on different measures: technical, allocative and economic efficiency. One definition in use for technical efficiency (TE) is 'the ability of a farm to use minimum feasible amounts of inputs to produce a given level of output' (Coelli et al., 2002; Dhungana et al., 2004; Rodríguez Diaz et al., 2004a). This input-oriented definition was chosen here to reflect the reality where more sustainable use of resources is an underlying objective (Speelman et al., 2007). Allocative efficiency (AE) on the other hand refers to the degree to which inputs are used in optimal proportions, given the observed input prices and the value of the outputs produced. Economic efficiency (EE) finally is the product of allocative and technical efficiency.

In practice different methods can be used to calculate these efficiency measures. In this study we use data envelopment analysis. DEA is a nonparametric method, that captures the above-described notion that a production unit can be considered more efficient if it is employing less input than another to produce the same amount of output. It is a systems approach in which the relationship between all inputs and outputs is taken into account (Raju and Kumar, 2006). Moreover only some minor adjustments to the basic model are needed to allow the calculation of economic or allocative efficiency.

2.2. The DEA models

In DEA simultaneously a production frontier is constructed and efficiency measures are obtained. The frontier surface is assembled piecewise by solving a sequence of linear programming (LP) problems, one for each farm and relating each farm to this frontier yields an efficiency level. As such a frontier, which envelops the observed input and output data of each farm, is created by the observations.

The DEA model for calculating technical efficiency is presented in equation 1 for a case with K inputs and M outputs for each of the N farms. For the i-th farm, input and output data are represented by the column vectors x_i and y_i, respectively. The KxN input matrix, X, and the MxN output matrix, Y, represent the data for all N farms in the sample.

$$Min_{\theta\lambda}\theta, \qquad (1)$$

subject to
$$\begin{aligned} & -y_i + Y\lambda \geq 0, \\ & \theta x_i - X\lambda \geq 0, \\ & N1'\lambda = 1, \\ & \lambda \geq 0 \end{aligned}$$

Where θ is a scalar, N1 is a Nx1 vector of ones, and λ is an Nx1 vector of constants. This model is solved once for each farm. The value θ, a score always lying between zero and one, is the technical efficiency score for the i-th farm. With one indicating that the farm lies on the frontier and is efficient. It should be noted that by including the convexity constraint (N1'λ=1), equation 1 constitutes the variable returns to scale (CRS) specification. Without that constraint the constant returns to scale (VRS) specification would be obtained. Using the constant returns to scale specification it is assumed that farms are operating at their optimal scale (Fraser and Cordina, 1999). Coelli (1996) established a relationship between the two measures showing that the scale efficiency of a farm can be obtained by dividing TE_{crs} by TE_{vrs}. In the remaining of this paper the constant returns to scale specification will be used.

Another useful characteristic to capture is a farms' success in choosing an optimal set of inputs given the set of input prices. This is done be calculating the allocative efficiency. Based on the technical and economic efficiency the allocative efficiency can be determined residually as AE=EE/TE. Economic efficiency itself is calculated in two steps. First a cost-minimizing vector of input quantities given the input prices is determined using following model (equation 2).

$$Min_{x_i^* \lambda} w' x_i^*, \qquad (2)$$

subject to
$$-y_i + Y\lambda \geq 0,$$
$$x_i^* - X\lambda \geq 0,$$
$$N1'\lambda = 1,$$
$$\lambda \geq 0$$

Where w_i is a vector of input prices for the i-th farm and x_i* (which is calculated by LP) is the cost-minimizing vector of input quantities for the i-th farm, given the input prices w_i and the output levels y_i. The other symbols are the same as in the model for the calculation of the technical efficiency.
Then in the second step economic efficiency (CE) of the i-th farm is calculated as the ratio of the minimum cost to the observed cost (equation 3)

$$CE = w'_i x_i^* / w'_i x_i \qquad (3)$$

With the allocative and technical efficiency of each farm calculated, a model to estimated the impact of changes in the water price can now be constructed.

2.3. Simulating adjustments in input and output vectors

The information from the efficiency analysis above is now used to model the effect of water price changes on the input vector. The rationale is similar to that of Jonasson and Apland (1997) when they incorporate frontier technology and inefficiencies in the mathematical programming of a sector model. By introducing the efficiency information, representation of the production technology is improved. Moreover, the farm level accounting data to create the technology frontier are relatively easy to collect.

The underlying assumption for this second step is that farmers will adjust their water use and input mix in response to the introduction of water charges, because relative prices have changed. It is assumed however that in the short run this will not have a direct effect on their overall levels of efficiency as they were defined above. This is confirmed in a study by Maniadakis and Thanassoulis (2004). When they decomposed productivity changes in Greek hospitals between two time periods, they were able to clearly distinguish the effects of changes in allocative and technical efficiency, changes in the technology of production and changes caused by shifts in input prices. They showed that shifts in input prices cause changes in input use without changing allocative efficiency.

The simulation model of this study uses thus the observed technology to estimate a new input vector for each farm, forcing the farms to maintain the same allocative and technical efficiency levels, while a new price vector is introduced. The model is an adjusted version of the allocative DEA model.

$$Min_{x'^{*}_{i}\lambda}\, w'_{new} x'^{*}_{i} , \tag{4}$$

subject to

$$- ysim_{i} + Y_{alfron}\, \lambda_1 \geq 0, \tag{5}$$

$$x'^{*}_{i} - X_{alfron}\, \lambda_1 \geq 0, \tag{6}$$

$$- ysim_{i} + Y_{fron}\, \lambda_2 \geq 0, \tag{7}$$

$$\theta_{CRS}\, xsim_{i} - X_{fron}\, \lambda_2 \geq 0, \tag{8}$$

$$\frac{w'_{new}\, x'^{*}_{i}}{w'_{new}\, xsim_{i}} = EE , \tag{9}$$

$$ysim_{i} = y_{i} , \tag{10}$$

$$\lambda_1 \geq 0 \tag{11}$$

$$\lambda_2 \geq 0 \tag{12}$$

Where w'_{new} is the new price vector for each farm and x'^{*}_{i} is the cost-minimizing vector of input quantities for the i-th farm given these new prices. $xsim_i$ is the simulated input vector, which maintains each farms’ technical and allocative efficiency. λ_1 and λ_2 are Nx1 vectors of constants. θ_{CRS} is the technical efficiency level and EE is the economic efficiency level of each farm determined in the first step. X_{alfron} and Y_{alfron} are variables equal to the simulated input vector and output vector, respectively for farms with an economic efficiency of 1 in the first step. They are set equal to a linear combination of the original points forming the efficiency frontier. X_{fron} and Y_{fron}, on the other hand, are parameters that are equal to the input vector and output vector of farms for which technical efficiency was found to be 1 in the first step. In this way, the input frontier and output frontier from the first step are introduced into the model in constraint (5) up to (8). Constraint (9) equals the economic efficiency given the new prices with the economic efficiency under the original prices and constraint (7) and (8) make sure that the technical efficiency is maintained. Constraint (10) was introduced to make ensure that scale of operations remains equal between the two steps. To reflect the situation that farmers start adjusting an existing input mix, the original vectors x_i were used as starting values in the simulation.

2.4.Data collection

Data was collected from small-scale irrigation schemes situated in Zeerust Municipality (North-West Province, South Africa) from July to September 2005. The municipality is located in North West Province, sharing a border with Botswana. Agriculture is an important economic activity in Zeerust, where unemployment is high (Zeerust Local Municipality, 2004). Questionnaires were used to collect data, with a total of 60 farmers interviewed, spread over 13 small-scale irrigation schemes. Extension staff of the North West Province Agricultural Department acted as interpreters. Random sampling was applied in selecting schemes and individual farmers, but representativeness was maintained by matching the number of respondents from each scheme with the number of farmers operational within them.

During the interviews information was gathered on quantities and costs of inputs used in production, quantities and values of outputs and the quantity of water consumed. In general the farmers in the study area do not keep records of their farming activities, so data gathered during interviews was based on recollections of farmers. The expert knowledge of the extension staff was used as a supplement to the recollections of the farmers, something that was particularly helpful for the estimation of the water use and the prices of their produce. Using the quantities and corresponding prices of the different outputs a monetary value for the total output was calculated. The inputs considered in the efficiency analysis include land, irrigation, labour, fertilizers and pesticides (table 1).

Table 1 Descriptive statistics on outputs and inputs used in efficiency analysis.

	Unit	Average	St. dev.	Minimum	Maximum
Output	rand[1]	2816	11348	150	87200
Inputs					
Land	ha	0.16	0.40	0.01	2.8
Water	m³	1287	3299	82.9	2215
Labour	man days	29	76	5.6	599
Expenditure on pesticides	rand	72	82	0	360
Expenditure on fertilizers	rand	64	91	0	487

3. Results

3.1. Efficiency analysis of small scale irrigators in South Africa

The three efficiency measures described above (technical, economic and allocative efficiency) are calculated using the CRS specification. Table 2 gives the frequency distribution of the efficiency estimates obtained. The average technical efficiency is 0.51 indicating that substantial inefficiencies occur in farming operations of the sample farm households. Allocative and economic efficiency are even lower, with an average value of 0.26 and 0.14 respectively. These scores indicate that farmers could considerably reduce costs by taking more notice of relative input prices when selecting input quantities. Such low allocative and economic efficiency values were also found by Bravo-Ureta and Pinheiro (1997) for peasant farmers in the Dominican Republic and by Vincente (2004) for crop production in some regions in Brazil. In South Africa these low values can be linked to the reported poor economic performance of the small-scale irrigation schemes in general (Perret, 2002).

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[1] At the time of the data collection the exchange rate was 1 Rand = 0.1504 US$

Table 2. Technical, economic and allocative efficiency under constant returns to scale specification (n=58[a])

	TE		CE		AE	
Efficiency score (%)	N° farms	% of farms	N° farms	% of farms	N° farms	% of farms
0-10	0	0	29	50	6	10
10-20	10	17	20	34	13	22
20-30	3	5	5	9	16	28
30-40	6	10	1	2	17	29
40-50	10	17	2	3	3	5
50-60	10	17	0	0	2	3
60-70	7	12	0	0	0	0
70-80	4	7	0	0	0	0
80-90	1	2	0	0	0	0
90-100	3	5	0	0	0	0
100	4	7	1	2	1	2
Average score	0.51		0.14		0.26	

[a] Two observations were removed from the sample because information was incomplete

3.2. Illustrative examples of simulation method

This section illustrates the method firstly using a simple numerical example and then it is applied to the South African data set.

Simple numerical example

Decision Making Units (DMUs) A-H in table 3 use two inputs (X_1 and X_2) to produce a single output (Y). For simplicity it is assumed that all units face the same input prices (P_1 and P_2), which are equal to 3 for both inputs. Table 3 and figure 1 show that the technical efficiency frontier at the starting situation is formed by DMUs A, B, C and D. Moreover at the original prices DMU A is allocative and economic efficient, with cost boundary 1 (representing the minimum cost of securing a unit of output) tangent to the technical efficiency frontier. We can now use the model described in section 2.3 to estimate effect of price change. To introduce the economic logic of negatively sloped demand curves into the model an extra constraint was imposed. An increase in the price of an input can not lead to higher use of this input. For calibration, the model was first run maintaining the original prices, as required this resulted in retrieving the original data points.

Assume now that in period 1 the price of input 1 increases to 7 for all units. This change in relative prices of inputs 1 and 2 causes the slope of the cost boundary to alter (cost boundary 2). As a result technical efficient DMUs will move on the efficiency frontier maintaining their level of economic efficiency. DMU A for instance moves from the point A to the point A’, where the new cost boundary is tangent to the frontier. DMU B moves from point B to point B’ and the preservation of the economic inefficiency here can be graphically shown as 0B/ 0B0 = 0B’/0B’0.

Table 3. Numerical example data

	X_1	X_2	Y	P_1	P_2	TE	AE	P_1’	X_1’	X_2’
DMU A	3	3	1	3	3	1	1	7	2	5
DMU B	5	3	1	3	3	1	0.75	7	4.2	3
DMU C	2	5	1	3	3	1	0.857	7	2	6.6
DMU D	2	8	1	3	3	1	0.6	7	2	11.4
DMU E	4	4	1	3	3	0.75	1	7	2.7	6.7
DMU F	6	4	1	3	3	0.75	0.8	7	5.2	4
DMU G	4	5	1	3	3	0.692	0.962	7	4	5.2
DMU H	3	7.5	1	3	3	0.67	0.857	7	3	9.9

Summarizing, technical efficient DMUs move along the frontier, maintaining their economic inefficiency level, but changing the input mix. Similar to the DMUs on the frontier, DMUs with a TE smaller than 1, stay at the same technical and economic efficiency level. For all DMUs the increase in price of input 1 increases the relative use of input 2. It should also be noticed that maintaining production at the same level incurs significantly higher costs. Costs at cost boundary 2 are 29, compared with 18 at boundary 1.

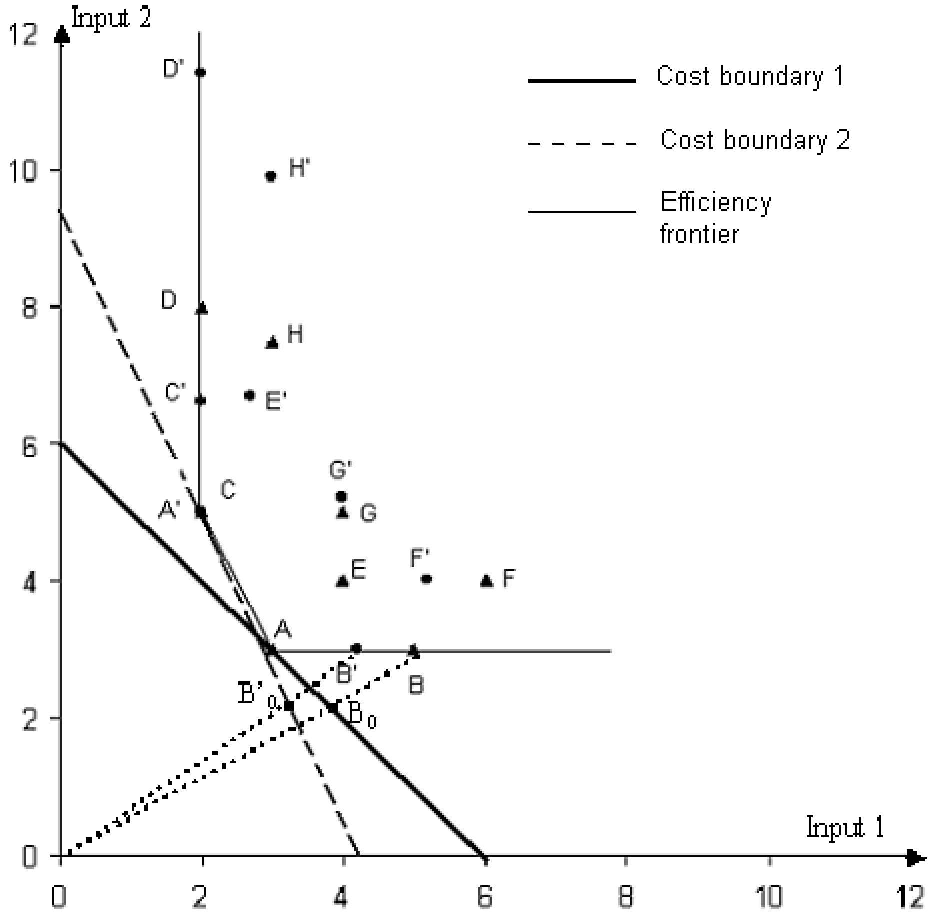

Figure 1: Simulating effect of relative price changes in a simple numerical example

Application to the South African farm budget dataset

The simulation model described in section 2 is now applied to the South African farm budget dataset. The original situation, where water is a free input, is changed by introducing a water price of 0.2011R/m³. This is the water price proposed for agricultural use by the Department of Water Affairs and Forestry of South Africa in the region under consideration (DWAF, 2006). A first logical observation is that the new cost-minimizing input vector x'^{*}_{i} is characterised by a decrease in water use and an increase in the use of all other inputs similar to the example above and in line with classical economic theory (table 3). This implies that costs connected with this cost-minimizing vector are higher than in the original situation, not only because water is no longer free, but also because the use of the other inputs is higher. Results furthermore show that only a minority of the farms (7% of the sample) respond to the change in water price by lowering their water use. Because these farms are using a lot of water and decrease their water use substantially (with 54% on average), total water saving is 22%, which is considerable.

Table 3 Effect of introduction of a water price

Change in input use		% farms with this change in the cost minimizing vector	% farms with this change in the input vector
Water	Increase	/	/
	Decrease	100%	7%
	No change	/	93%
Land	Increase	100%	64%
	Decrease	/	22%
	No change	/	14%
Labour	Increase	100%	51%
	Decrease	/	46%
	No change	/	3%
Fertilizer	Increase	100%	69%
	Decrease	/	19%
	No Change	/	12%
Pesticide	Increase	100%	72%
	Decrease	/	17%
	No Change	/	10%

Effect on the use of other inputs is mixed. For every input a majority of the farms increases its use, but many farms decrease the use of labour. This can be explained as follows: because part of the allocative inefficiency is already captured by the water input (maintaining the original water use level is allocative inefficient if the water price increases), the use of the other inputs should move closer to the allocative efficient level of the cost-minimizing vector, which for some inputs leads to a net decrease. Production costs also increase as a result of the introduction of the water price, with water making up on average 10% of the new production costs. Here, the model still requires changes to better reflect farmers behaviour, because currently for 2/3 of the farmers costs become even higher than output. Nevertheless even in the current form, results of the simulation are in line with those of Gómez-Limón and Berbel (2000) and Yang et al. (2003) demonstrating an intrinsically weak response of water use behaviour to price signals and a significant loss in farm income. Moreover corresponding to Gómez-Limón and Riesgo (2004) it is revealed here that farmers' response can be very different depending on the elasticity of their demand.

4. Conclusions

Water pricing is often seen as an important tool to improve efficiency of water use. Several authors however have warned of the limited effect in terms of water saving and the even negative economic and social side effects of this policy. Given the increasing pressure to release water for other uses and to find ways in which to improve irrigation performance, there is an urgent need for methodologies that allow estimating the effects of introducing or raising a water price.

This study uses a novel two-stage application of Data Envelopment Analysis (DEA) to simulate the effect of changes in water price. First a simple numerical example shows that the results of the simulation model are in line with classical economic theory, with a price change causing a change in the ratio between the inputs. When applied to the water-pricing scenario in South Africa, an important finding is that in this analysis most farms do not react to the introduction of the water price by decreasing their water use. Production costs however increase substantially, which seems to confirm the negative side effects of water pricing. Results however also showed that changes to the model to more realistically simulate farmers' behaviour are still required. Firstly outputs should be made flexible to enable farmers to reduce scale of operations. Secondly a version of the model accounting for variable returns to scale should be elaborated. Another option we are currently investigating is the use of the efficiency information from the first step to establish a set of perceived prices for the different inputs. This would give us more detailed insight in the attitude of the farmer towards each individual input, which can then help to estimate the impact of price changes. Finally, if the current shortcomings of the methodology can be eliminated, the use of observed technology frontiers in simulation models can clearly improve estimation of price change effects.

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