Quantifying the uncertainties in estimating the heterogeneous effects of carbon taxes on labor, land, water, and fertilizer use in US agriculture

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ABSTRACT

Potential carbon taxes will have spatially heterogeneous impacts on agriculture. The magnitude of impacts depends on 1) the direct and indirect share of energy in production costs, 2) the responsiveness of agricultural markets to price changes, and 3) the degree of possibility of reallocation of resources. This study introduces a theoretical economic framework for the analytical evaluation of a carbon policy. Then the parameters of the model are empirically estimated. Finally, the impacts of three scenarios of carbon policies are computed and uncertainty in the results is discussed. The focus of this study is on irrigation and nitrogen fertilizer as energy-intensive inputs. Then the consequences for land and labor markets are analyzed.

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1 Summary

Introduction. Potential carbon taxes will have spatially heterogeneous impacts on agriculture. The magnitude of impacts depends on 1) the direct and indirect share of energy in production costs, 2) the responsiveness of agricultural markets to price changes, and 3) the degree of possibility of reallocation of resources. This study introduces a theoretical economic framework for the analytical evaluation of a carbon policy. Then the parameters of the model are empirically estimated. Finally, the impacts of three scenarios of carbon policies are computed and uncertainty in the results is discussed. The focus of this study is on irrigation and nitrogen fertilizer as energy-intensive inputs. Then the consequences for land and labor markets are analyzed.

Significance and contribution. There is a rich literature on quantifying the economic impact of carbon policies (Chepeliev and van der Mensbrugghe, 2018; Dumortier and Elobeid, 2021; Golub et al., 2013; Hafstead et al., 2018; Lin and Jia, 2018; Schneider and McCarl, 2005). Most of these studies are done at the regional or aggregate sub-regional scales. However, the implications of such policies are expected to vary across space as the production structure is spatially heterogeneous and does not follow a normal distribution. This can be mainly due to differences in the cost structure and energy intensity of productions. This paper provides county-level empirical evidence to show the significant differences in the cost shares, agricultural production structure, and supply elasticities of land and water (Doelman et al., 2022; Haqiqi and Hertel, 2019; Beier et al., 2023). This implies that some communities will be affected more than other communities and the national average may be misleading for local impacts. This study tries to provide a framework to improve our understanding of the county-level impacts of climate policies. This can help form local policies to protect the most vulnerable and affected communities. It can also help the research community in understanding the likely changes in the economic geography and relocation of activities.

Theoretical model. This study follows Costinot et al., (2016) to develop a partial equilibrium international trade model assuming n local markets with uniform farms within each unit. Each unit produces a slightly different commodity. The consumers (domestic and international) have Armington-type preferences with imperfect substitution between these varieties. Local production is modeled assuming a constant elasticity of substitution function in agricultural production and a constant elasticity of transformation for land allocation. Agricultural inputs are land, energy, energy-intensive materials, and a composite of other inputs. The land is allocated to rainfed and irrigated through a constant elasticity of transformation function. Labor decides about the work location based on local and remote agricultural wages assuming a constant elasticity of transformation function. The price of energy and energy-intensive materials are determined in the international market, but the price of land is determined at each local market. The model is solved analytically, and the implication of equilibrium conditions are discussed.

Empirical estimation. This study follows the SIMPLE-G framework to parameterize the model based on the US Department of Agriculture Census of Agriculture for 1997, 2002, 2007, 2012, and 2017. The county-level information is obtained for cropland area, cash rents, and expenditure shares (energy, labor, fertilizer, land, and other inputs).

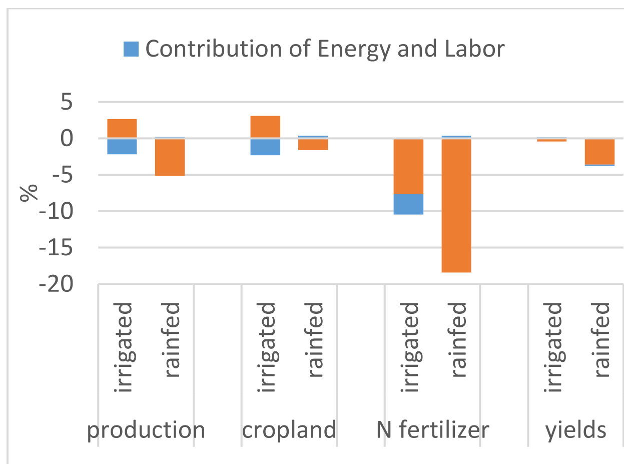
Simulations. The carbon pricing scenarios are obtained from the ENVISAGE model quantifying the final change in prices at the national level for labor wages, energy products, and fertilizer and used to quantify the likely changes in the spatial pattern of water and land use given the proposed shocks in input prices. This study considers four scenarios of carbon pricing ($50, $100, $150, $200) from the ENVISAGE model, the Environmental Impact and Sustainability Applied General Equilibrium Model (van Der Mensbrugghe 2018). The ENVISAGE Model is a general equilibrium multi-sector model designed to analyze a variety of issues related to the economics of energy policies and climate change. This makes it an appropriate tool for this analysis. For each pricing scenario, the final impact on the commodity prices is calculated. The commodities used in this study are ammonia, labor wages, natural gas, electricity, and petroleum products.

Uncertainty quantification. This study compares the Monte Carlo analysis and Sobol's method in uncertainty quantification (Harenberg et al., 2019; Helgeson et al., 2021; Nossent et al., 2011). The findings show the significance of uncertainty propagation from substitution, transformation, and supply elasticities.

Results. The goal of this study is to identify where and why employment and irrigation may decline or increase. The discussion includes the implications for the job market and water resources. Figure 1 summarizes preliminary results using a simplified framework. As a result of a $100 carbon tax policy, the US average price of crop production increases by 2.3%, and production declines by 3.0%. The average application of nitrogen fertilizer decreases by 16.0% and the groundwater withdrawal increased by 0.9%. The increase in water withdrawal along with a decline in fertilizer application indicates a substitution from fertilizer to water at the national level. The right panel also shows a substitution from rainfed to irrigated agriculture. Note that the figures also decompose the impact to show the contribution of changes in fertilizer price and energy price. While the increase in energy price discourages irrigation, the change in N fertilizer costs is so high that leads to an increase in irrigation. The full paper discusses the sources of heterogeneity and local biophysical and economic factors leading to these findings.

	Contribution to change (%)	
	N Fertilizer	Energy and Labor
crop prices	1.8	0.5
crop production	-2.3	-0.7
cropland	-0.8	-0.1
N fertilizer	-15.7	-0.3
other ag. inputs	-1.3	-0.5

(a)



(b)

Figure 1. Preliminary results of $100 carbon pricing in the US.

2 Technical details

In addition to providing a new model and dataset, the main contribution of this study compared to Costinot et al (2016) is a unique structure to account for different degrees of factor and product mobility across space.

2.1 Theory

2.1.1 *Preferences and product heterogeneity*

While Costinot et al (2016) assume different crop commodities in their model, this study considers one composite crop output for each grid cell. Assume an economy consists of different-sized grid cells (as units of production) each producing a slightly different composite crop indexed by $g \in \Gamma = \{1, ..., G\}$. The degree of heterogeneity (similarity) of commodities is different, so the more similar commodities are put together in one category (e.g. grid cells with a higher share of fruits and vegetables). With this assumption, there are M categories of commodities consisting of varieties that are less different. These categories are indexed by $m \in \mathrm{M} = \{1, ..., M\}$. Let *Q* show the aggregate crop composite and *r* show an index for regions $r \in \mathrm{P} = \{1, ..., R\}$, a regional aggregator of crop categories will be:

$$Q_r = \left[\sum_{m \in r} (\beta_m)^{1/\lambda_r} (Q_m)^{(\lambda_r - 1)/\lambda_r} \right]^{\lambda_r/(\lambda_r - 1)} \quad (1)$$

$$Q_m = \left[\sum_{g \in m} (\beta_g)^{1/\gamma_m} (Q_g)^{(\gamma_m - 1)/\gamma_m} \right]^{\gamma_m/(\gamma_m - 1)} \quad (2)$$

where λ >0 denotes the elasticity of substitution between commodity groups (e.g. corn-dominant vs fruit-dominant); γ>0 is the elasticity of spatial substitution between grid cells in a similar group (crop category); β is the CES (constant elasticity of substitution) parameter. Within this structure, considering a single composite crop for each location provides computational convenience while keeping various degrees of product heterogeneity.

2.1.2 *Spatially resolved production technology*

Costinot et al (2016) assume a very simple production technology with labor and land. This study considers a more complicated production technology. There are four production inputs: fertilizer (*N*), labor (*H*), land (*L*), and water (*W*) for each grid cell *g*. By assumption, fertilizer is perfectly mobile, labor is imperfectly mobile, while land and water are immobile factors of production. So the nested CES production technology will be:

$$Q_g = \left[\alpha_{g,l'} \left(L'_g \right)^{(\sigma_g - 1)/\sigma_g} + \alpha_{g,h} \left(H_g \right)^{(\sigma_g - 1)/\sigma_g} + \alpha_{g,n} \left(N_g \right)^{(\sigma_g - 1)/\sigma_g} \right]^{\sigma_g/(\sigma_g - 1)} \tag{3}$$

$$L'_g = \left[\alpha_{g,l} \left(L_g \right)^{(\omega_g - 1)/\omega_g} + \alpha_{g,w} \left(W_g \right)^{(\omega_g - 1)/\omega_g} \right]^{\omega_g/(\omega_g - 1)} \tag{4}$$

where σ >0 denotes the elasticity of substitution between labor, fertilizer, and the land-water composite (L'); ω>0 is the elasticity of substitution between land and water; and α is the CES parameter.

2.1.3 *Equilibrium conditions for immobile inputs*

For land and water input markets are cleared at each grid cell. Here, there is an upward-sloping supply function with location-specific parameters.

$$L_g = \eta_g^L PL_g^{\mu_g^L} \quad (5)$$

$$W_g = \eta_g^L PW_g^{\mu_g^W} \quad (6)$$

where η is the shifter, PW is the value of water, PL is the land rent, and μ is the supply elasticity of land with respect to rents for grid cell g. The derived demand for land and water input in crop production is:

$$L_g = \delta_g^L \frac{Q_g}{A_g^L}\left(\frac{PL'_g}{PL_g}\right)^{\omega_g}\left(\frac{PQ_g}{PL'_g}\right)^{\sigma_g} \quad (7)$$

$$W_g = \delta_g^W \frac{Q_g}{A_g^W}\left(\frac{PL'_g}{PW_g}\right)^{\omega_g}\left(\frac{PQ_g}{PL'_g}\right)^{\sigma_g} \quad (8)$$

where $\delta > 0$ and $A > 0$ are the CES parameters and PQ is the unit production cost.

2.1.4 Equilibrium conditions for perfectly mobile inputs

For fertilizer input, markets are cleared at the regional level. Again, there is an upward-sloping supply function with region-specific parameters.

$$N_r = \eta_r^N PN_r^{\mu_N} \quad (9)$$

where η is the shifter, PN is the price of fertilizer, and μ is the supply elasticity. The derived demand for fertilizer is obtained by:

$$N_g = \delta_g^N \frac{Q_g}{A_g^N}\left(\frac{PQ_g}{PN_g}\right)^{\sigma_g}, g \in r \quad (10)$$

$$\begin{aligned} N_r &= \sum_{g \in r} N_g, \\ PN_g &= \varphi_g PN_r \end{aligned} \quad (11)$$

Here the market supply of fertilizer is equal to the sum of grid cell demands at a uniform regional price. In other words, all the grid cells face the same price change for fertilizer within each region distinguished by an index of transportation and trade margin φ.

2.1.5 Equilibrium conditions for imperfectly mobile inputs

For labor input, markets are cleared at the sub-regional level. There is an upward-sloping supply function with sub-region-specific parameters and a CET function for location decisions.

$$H_m = \eta_m^H PH_m^{\mu_H} \tag{12}$$

where η is the shifter, PH is the average wage rate, and μ is the supply elasticity. The CET-derived gridded labor supply is:

$$H_g = \zeta_g^H \frac{H_m}{\xi_g^H}\left(\frac{PH_m}{PH_g}\right)^{\psi_g} \tag{13}$$

where ζ , ξ are CET parameters. The CES-derived gridded labor demand is:

$$H_g = \delta_g^H \frac{Q_g}{A_g^H}\left(\frac{PQ_g}{PH_g}\right)^{\sigma_g} \tag{14}$$

$$H_m = \sum_{g \in m} H_g \tag{15}$$

Here the market supply of labor is equal to the sum of grid cell demands at sub-region m. In other words, all the grid cells face different wages but the supply of labor to each location depends on relative spatial wages.

2.2 Model

The computation framework follows the SIMPLE-G model family solved in GEMPACK (Horridge et al., 2018). SIMPLE-G is spatially resolved version of SIMPLE, based on SIMPLE, a Simplified International Model of agricultural Prices, Land use, and the Environment (Baldos and Hertel, 2014; Hertel and Baldos, 2016; Liu et al., 2017). The crop production technology follows Baldos et al, (2020). Labor market structure follows Ray et al, (2023). The additive CET (constant elasticity of transformation) for land allocation follows Haqiqi et al (2022) and Haqiqi et al., (2023b). The sub-regional market structure follows Haqiqi et al., (2023a). The nitrogen fertilizer modeling and parameterization follows SIMPLE-G-US (Liu et al., 2018; Sun et al., 2020).

2.3 Data

While previous SIMPLE-G works on gridded economic modeling in the United States have centered around the year 2010, the model of this study is calibrated based on the 2017 reference year following Haqiqi et al., (2023a).

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