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A Supply Chain Impacts of Vegetable Demand Growth: The Case of Cabbage in the U.S.

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ABSTRACT

A number of initiatives have been designed to address food insecurity problems in the U.S., particularly promoting increased consumption of vegetables. However, if the demand for vegetables increases, little is known regarding the impacts of increased demand on the structure of vegetable supply chain. A related relevant question is: if the demand for vegetable increases, what are the impacts on the structure and performance of the vegetable supply chain? As agriculture production often has lag periods in responding the market, what would be the impact in short term considering fixed supply? Furthermore, if the production capacity constraint is relaxed in the long run, where would additional supply originate to simultaneously satisfy the new demand and contribute to supply chain efficiency? To address these questions, we develop a spatially disaggregated transshipment model of the U.S. cabbage sector to assess the impact of a demand increase on the structure and performance of the cabbage supply chain. Our model provides insights of vegetable supply chain impacts on system-wide costs, regional wholesale prices, degree of self-reliance and food miles. The results of cost-minimizing production acreage expansion suggest that the supply chain may become increasingly interconnected nationally.

1. Introduction

In the United States (U.S.), the estimated daily intake of fruits and vegetables remains well below recommended levels, especially for dark green vegetables. This often results in deficient micronutrients intake (USDA ERS, 2012a). According to the U.S. Department of Agriculture (USDA) (2009), the estimated daily per capita intake of vegetables in the U.S. is 1.58 cups, while the recommended level is 2.60 cups. Vegetable daily intake is even lower for low income households, estimated at 1.43 cups of vegetables (USDA ERS, 2009). Also, low-income households tend to avoid reductions in food intakes by relying on fewer basic foods and by reducing the variety of their diets (Golan et. al, 2008).

Given the lower than recommended intakes, the past decade has seen a number of public and private initiatives aiming at increasing vegetable consumption. For example, U.S. public-private initiative “Fruits & Veggies - More Matters,” urges for greater vegetable consumption through promoting meal planning guidelines among U.S. households. The Supplemental Nutrition Assistance Program, which formerly known as the Food Stamp Program, provides food purchasing stipends for low-income households. Such initiatives can potentially increase demand in the future. Therefore, a relevant research question is: if the demand for vegetable increases, what are the impacts on the structure and performance of the vegetable supply chain? As agriculture production often has lag periods in responding the market, what would be the impact in short term considering fixed supply? Furthermore, if the production capacity constraint is relaxed in longer period of time, where would additional supply originate to simultaneously satisfy the new demand and contribute to supply chain efficiency? To address these important questions, we focus on the U.S. cabbage supply chain. Cabbage is a relevant case because it is one of the dark green vegetable that highlighted for its health benefits (Webmd, 2011). In addition, cabbage is widely consumed in the

U.S., and most consumption is met by domestic production. Lessons learned from cabbage can be applied to the analysis of other dark green vegetables.

In this study, we develop a transshipment model of the U.S. cabbage supply chain, including production, storage, and consumption segments, to assess the impacts of demand increase on supply chain structure. In addition, to understand how the demand growth affects the extent of regional self-reliance[1], we estimate the proportion of demand that is satisfied by the regional supply and the weighted average distance traveled by the commodity.

On the consumption side, we differentiate regional demand by three income levels: low, medium, and high income groups. Due to the fact that vegetable consumption level correlates with household income, we assign different base vegetable consumption values using the estimation of USDA (2009) where poorer consume less than richer. Then, we simulate the demand growth by assigning lower income groups with larger demand increments, considering that current interventions mainly target low-income household to improve their vegetable consumption.

Using the U.S. cabbage supply chain model, we evaluate the supply chain impacts of demand growth from two simulations. First, after employing the exogenous shock of demand growth, we analyze the impacts under fixed production. Second, following the identical exogenous demand shock, we explore the impacts with production responses. Specifically, the model identifies optimal supply locations to produce more cabbage on meeting the increased demand, where optimality refers to solutions that minimize total supply chain costs. Then, for these optimal supply locations, we loosen the farmland production constraints with extra farmland allowances and resolve the model until the retail price is offset back to baseline price. Since we consider the

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[1] We use the term "regional self-reliance" rather than "localization" in this study, since localization often presumes smaller geographical scale such as cities or towns, whereas we are referring to regions that is defined with the states of the U.S.

baseline retail price as an equilibrium market price, the second simulation resembles the market response on facing an increased demand in long term. Our study sheds light on how changes on vegetable demand can affect vegetable supply chain structure with both fixed and flexible production constraints as well as the implications for supply chain costs, changes on regional self-reliance, and retail prices paid by consumers.

2. Relevant Literature

Food and agricultural supply chains have received considerable attention from researchers in recent years. Studies that analyze food supply chain structure and performance can be broadly categorized into two major categories. One category focuses on evaluating interventions aimed at improving supply chain performance from various scopes, such as food safety, supply chain efficiency, etc. The other category emphasizes how exogenous shocks affect food supply chains' performance and structure. Our study falls in between, which by simulating an exogenous demand shock, we evaluate the corresponding changes in supply chain performance in multiple dimensions. Since one of the focuses of our study is to examine the extent of regional self-reliance, we also visit several supply chain research with the topic of localization in this literature review.

First, the overwhelming majority of researches studying the exogenous supply chain shocks address the supply-side shocks, such as climate change and changes in oil price. For example, studies suggest that climate change may affect the global aggregate food system significantly from crop production to changes in markets, food prices and supply chain infrastructure (Gregory et al., 2005,). Study also suggests that the impacts of climate change on food systems will be notably different among different regions and between poorer and wealthier populations (Vermulen et al., 2012). Oil price is also of concern as researchers evaluate how the changes in oil prices, strikes and blockades could have effect on the food system (Jones, A., 2002).

A number of studies analyze the energy intensity of food production, distribution, and marketing systems in depth during the oil crisis of 1973, when there’s uncertainty of price and supply of crude oil (Olabode et. al., 1977, Hirst, E., 1973, Brown and Batty 1976). These studies consider the dependency of the food system on fuels derived from crude oil and possible disruptions in food supply.

In contrast to the great number of supply-side research, fewer address on how the demand-side changes affect food supply chain. One study from Godfray et al. (2010) states that demand-side drivers such as population growth, shifting patterns of consumption, urbanization, and income distribution is changing the global food system, and the challenge is to improve the food system to meet this increasing demand of food. They conclude that though there is no simple solution but different strategies such as closing the yield gap, increasing production limits, reducing waste, and changing diets can contribute to meet this challenge. Pingali (2007) discusses the transformation of the Asian food supply chain systems in response to Westernization of diets. He reveals that the traditional food supply chain cannot meet the growing demand for diet diversity and states that a modern and vertically integrated food supply chain linking input suppliers, producers, processors, distributors and retailers is needed to meet the changing demand requirements. However, facing the potential increase of food demand, there is very little empirical evidence regarding the potential costs on food supply chain associated with the demand growth.

For other food supply chain research, there is a stream of literature addressing localized food supply chain, such as evaluating consumer preferences toward local foods (Sirieix et al., 2008, Thilmany et al., 2008, Onozaka et al., 2010, Zepeda and Deal, 2009), and the willingness to pay for specialized or locally-grown fruits and vegetables (Conner et al., 2009, Moser et al., 2011, Senyolo et al., 2014 and Toler et al., 2009). Food localization has been not only researched from the consumer side but also various aspects from the production and supply side. Atallah et al. (2014) found that, localization may occur without increases in total supply chain costs or consumer prices, which contrasts with the findings that localization can impose relatively large cost re-allocations across supply chain segments, regions and products and large increases in consumer prices (Nicholson et al., 2011). There are also studies and compares the environmental indicators between conventional and shorten food supply chain (Coley et al., 2009, Marletto & Sillig, 2014). Weber and Matthews (2008) compared the GHG emissions between local food production and long-distance distribution and shows that changing diets is a more efficient strategy to reduce GHG emissions than localizing food supply chains.

In sum, from the current food supply chain literature, very little is known about the impacts of vegetable consumption changes on the food supply chain structure, and how the change will affect the level of localized food chain at the region level. By developing and analyzing an optimization model of the U.S. cabbage sector, we contribute to the literature in understanding the possible supply chain impacts of a growing vegetable demand in various dimensions, such as costs, prices, and the extent of regional self-reliance, etc.

3. Methods

We develop a spatially-disaggregated, inter-temporal supply chain transshipment model of the U.S. cabbage sector, including production, storage and transportation. In this study, we consider cabbage for both fresh market and coleslaw, but not processed cabbage used for the production of sauerkraut. The baseline model of the U.S. cabbage supply chain is constructed with a combination of data and mathematical programming equations. In this section, we elaborate model formulation, data employed, and the simulations with fixed production and with supply response, to estimate the impacts of increased demand on the supply chain structure.

3.1.Model Formulation

The U.S. cabbage supply chain model is constructed as an inter-temporal transshipment problem. The problem’s objective is to find the optimal product flow (in million pounds) at each season *t* (winter, spring, summer and fall) that minimizes the total supply chain costs (equation 1.1-1.3). The optimization problem is formulated mathematically as follows:

(1) Minimize Total Supply Chain Costs= Total Production Costs + Total Storage Costs + Total Transportation Costs

(1.1) $\text{Total Production Cost} = \sum_t \sum_a \left[\frac{(\sum_b AB_{t,a,b} + \sum_c AC_{t,a,c})}{yield_a} * PduCost_{t,a}\right]$

(1.2) $\text{Total Storage Costs} = \sum_t (\sum_a \sum_b (AB_{"T",a,b}, * StoreCost_{"T+1",b}) + \sum_a \sum_b (AB_{"T",a,b}, *$
$StoreCost_{"T+2",b}) - \sum_b \sum_c (BC_{"T+1","T",b,c}, * StoreCost_{"T+2",b}))$

(1.3) $\text{Total Transportation Costs} = \sum_t \sum_a \sum_c (Tcost * AC_{t,a,c} * MileAC_{a,c}) +$
$\sum_t \sum_{t_{in}} \sum_b \sum_c (Tcost * BC_{t,t_{in},b,c} * MileBC_{b,c})$

Subject to:

(2) $\sum_b AB_{t,a,b} + \sum_c AC_{t,a,c} \leq Land_{t,a} * Yield_a$

(3) $\sum_a AC_{t,a,c} + \sum_b \sum_{t_{in}} BC_{t,t_{in},a,c} \geq DemandQuantities_{t,c}$

(4) $\sum_a AB_{"T",a,b} * (1 - StorageLoss) \geq \sum_t \sum_c BC_{"T+1","T",b,c}$

(5) $BC_{"T","T",b,c} = 0$

(6) $BC_{"T+3","T",b,c} = 0$

(7) *Land production ≥ 75% of land available*

(8) All choice variables are non-negative

The indices t, a, b, and c indicate seasons, supply locations, storage locations, and demand locations, respectively. Product flows are represented by three variables, $AC_{t,a,c}$, $AB_{t,a,b}$, and $BC_{t,t_{in},b,c}$. That is, cabbage produced at each season can be either shipped directly from supply location a to demand location c ($AC_{t,a,c}$); or it can be shipped from supply location a to storage location b ($AB_{t,a,b}$), and then shipped from storage location b to consumption location c in the following two seasons, represented as $BC_{t,t_{in},b,c}$, where t_{in} is a subset of t indicating the season in which cabbage enters into storage.

Equation 1.1 represents total production cost, which is calculated using $yield_a$(estimated yields in million pounds/acre), and $PduCost_{t,a}$ (the average total production costs per acre), at each supply location. Equation 1.2 indicates total storage cost which is calculated using $StoreCost_{t,b}$, average storage costs of storage location b at season t. We only consider storing cabbage for up to two seasons given the practices used in the industry. Capital T denotes one element in the set t, which can be either the spring, summer, fall or winter season. The indices $T+1$ and $T+2$ denote the following one and two seasons after season T, respectively. Total transportation cost is shown in equation 1.3, where *Tcost* is the average unit transportation costs (dollars for one million pounds/mile), $MileAC_{a,c}$ and $MileBC_{b,c}$ are the distances in miles between supply or storage locations and demand locations.

The land constraints (equation 2 and 7) ensure that the cabbage shipped out from each supply location does not exceed the production capabilities at that location in each season, while at least 75% of the given land is used to fit the reality. Seasonal demand constraints (equation 3), for their part, ensure that the quantities shipped to each demand location met the quantities demanded in that demand location in each season. The storage loss is measured by the reduction in quantity supplied (equation 4), where *StorageLoss* is the percentage loss for both common and cold storage. Equation 5 and 6 ensure that all stored cabbage is stored for at most two seasons, and cabbage cannot be stored and shipped out from storage locations within the same season, which is consider as direct shipment to consumption locations. Equation 8 states that all choice variables have to be non-negative.

3.2.Supply, storage, transportation, and consumption data

The supply-side data employed to calibrate the model includes seasonal acreages allocated to cabbage, seasonal production costs and yields at each supply location; storage capacity and storage costs at each supply location. We identify total 20 supply locations in the model, which includes 15 main production states of cabbage in the U.S (Figure 1) and accounts the net imports from Mexico and Canada to the U.S. According to Economics Research Service (USDA, 2010), the U.S. imported 137 million pounds of cabbage from Canada and Mexico in 2010, which accounted for about 12% of annual consumption. In addition, the U.S. exported about 60 million pounds of cabbage mainly to Canada and Mexico in 2010, which accounted for about 3% of total cabbage production in the U.S. The state level production is disaggregated whenever the data allows doing so.

In addition to the supply nodes, the model has total 100 demand locations, including Canada as one demand location in the spring season to account the net exports from U.S. to Canada in that season. We use the large metropolitan statistical areas (MSAs) (US Census, 2010) to define the large demand locations in the U.S. (Figure 1).

Insert [Figure 1: U.S. Supply and Demand nodes]

The cabbage growing seasons differ among production regions. For example, California can provide year-round production, while cold climate regions, such as New York, can only produce in the summer and fall seasons. Table 1 presents the estimated seasonal acreage and yields of the U.S. supply locations, and Figure 2 illustrates the sizes and geographical comparison of the domestic supply locations in each season. We adjusted the production cost estimates by region taking into account different input costs (wages, land rent, electricity, gasoline, fertilizer, herbicides, etc.) from crop budgets published by the International Agricultural Trade and Policy Center, University of Florida (2009).

Insert [Table 1. Estimated U.S. cabbage acreage and yield at each domestic supply location at each season]

Insert [Figure 2. Aggregated U.S. cabbage supply locations and the sizes of land available in each season]

Storage costs are obtained from a survey conducted among cabbage growers and program leaders of Cornell Cooperative Extension. There are two types of storage for fresh cabbage: regular storage and cold storage. Regular storage is widely used by growers. In this method, cabbage is stored in a shaded area with fresh air and the product can be stored for up to 11-15 weeks. Cold storage is employed primarily in the summer harvest season and can extend the storage time to about 6 months.

Storing cabbage implies product losses resulting from shrink and trim loss. According to industry experts, the shrink loss is about 15% for regular storage and 8% for cold storage, and the trim loss is about 10% for regular storage and 16% for cold storage (Hoepting & Klotzbach, 2012). In the model, we have assumed a total loss of 25% of the quantity after stored. Also, due to the characteristics of fresh cabbage (bulkiness, weight, etc.), the product is generally stored in facilities located near the production locations. Therefore, we omit the transportation costs between production locations and storage facilities in this study. The transportation costs only account for the distance traveled from production or storage locations to demand locations.

Regarding the transportation cost, it is calculated using the distance traveled and the average truck rates. We employ ArcMap of the Geographic Information System software, to calculate the minimum distances between each production/storage location and each demand location. We use USDA's quarterly agricultural refrigerated truck rates (USDA-AMS, 2013) to compute the shipping costs and assumed 45-lb crate is used in transporting cabbage.

For the consumption data, we first estimate the regional baseline consumption using per capita disappearance and population of the MSAs (USDA-ERS, 2012b; US Census, 2012). The regional baseline consumption value is then adjusted between three income groups, low, middle, and high-income, using the estimated dark greens per capita consumption from USDA (2009) and population share of three income groups for each MSA (US census, 2012). Align with the definition of US Census (2012), we define three levels of income group as the following: annual earning lower than \$15,000 as low income, \$15,000- \$100,000 as middle income, and above \$100,000 as high income. The aggregated regional baseline consumption values are shown in next section (Table 3). Lastly, the seasonal consumption difference is calculated using the monthly shipment of U.S fresh market cabbage, since the consumption seasonality correlates with seasonal flow of the market shipment (Table 2).

Insert [Table 2. Seasonality of fresh cabbage shipment, as a proxy of demand seasonality]

3.3. Simulations of an exogenous demand growth

According USDA (2013), the average per capita consumption of vegetable for adults is 0.21-0.29 cups per day, which is well bellowed the recommended level. Comparing to the domestic consumption average, the deficiency in dark green vegetable intake are larger for low and middle income groups, which only reach 69% and 89% of national average consumption, respectively. As current domestic interventions of promoting vegetable consumption mainly target at lower income households, we simulate the exogenous shock of the demand growth on the low and middle income groups in our model. Using the estimated dark green vegetables per capita consumption, we employ an exogenous increase in low and middle income groups' consumption. The values of exogenous demand growth in low and middle income groups are 50% and 13% additionally from the baseline value. This percentage increase is calculated by taking the difference between current consumption and national average consumption of estimated dark green vegetable per capita annual consumption (USDA, 2009). In other words, we are looking at a potential demand growth that allows low and middle income groups to reach the current national average consumption value. In this case, lower income group has a larger increment of demand growth than middle income, whereas the consumption value of high income group remains the same as baseline value. Table 3 shows the regional-aggregated income structure along with the scale of simulated exogenous demand shock. The total national consumption increase in this simulated shock is about 10-11%.

Insert [Table 3. Income structure and consumption by region]

Our analysis consists of two alternative simulations for this demand shock to demonstrate the possible impacts in short and long term. In the first simulation, we employ the demand shock under existing supply capability. That is, we assume fixed farmland in the model after the demand growth. This is reflecting the short term supply chain impacts, since agriculture production often has lag periods in responding the market and the high opportunity costs in promptly shifting land to different crops, etc. For the second simulation, following the same demand shock, we evaluate impacts with farmland expansion so that production capacity is flexible. We select the optimal supply location to increase production until the national average wholesale price is offset back to the baseline value. The second simulation is elaborated in the following.

First, as fixed price elasticity is assumed in the model, the wholesale price increases when there is an absolute demand increase. Therefore, under a perfect-competitive market, the national supply responses will be following the cost-minimizing solutions to offset the higher price. In other words, after demand increases, there will be reallocation of farmland from other crops to cabbage due to the profits in cabbage production. When the wholesale price is offset back to the baseline value, which considered as the price equilibrium, producer will stop shifting land from other crops to cabbage. Since we are assuming a perfectly competitive market, the seasonal shadow price of each demand location can be viewed as the seasonal wholesale prices at each demand location.

Secondly, in order to solve for the optimal supply locations to increase production that can minimize the national supply chain costs. The procedure used here follows Atallah et al., (2014). After the demand shock, the model provides resulting seasonal marginal values of each supply location and seasonal shadow prices of each demand location. The seasonal marginal values of each supply location can be interpreted as the decrease of total supply chain costs that could be brought if an additional acre is allocated to that particular supply location in that season. These marginal values of supply locations can be viewed as the indicators of the land values at each supply location in each season. Thus, the second simulation with land expansion simulations are done by selecting the location-season with largest absolute marginal value, then we increase the land available to the limit which the current marginal value changes and resolve the model recursively. We follow this procedure until the total acreage expansion can offset the higher wholesale price to the baseline value. In addition, we impose an additional constraint of maximal extra 25% farmland increase for each supply location to align with the scale of production in reality. This second simulation with optimal production expansion resembles the long term market responses after facing a demand increase.

3.4. Supply chain impact measures

We examine the impacts of simulations described above on several key supply chain structural indicators at national and regional level. For example, the supply chain costs and the average wholesale price at each demand location, which is used as a proxy for retail price, given that retail prices generally equals to wholesale price plus a markup of a retail operator.

We estimate changes in the share of regional production in regional consumption using a *Self-Reliance* index, which is a degree that the region is self-reliable to meet the region's cabbage demand. Mathematically,

$$\text{(9)} \qquad \text{Self-Reliance} = \frac{\sum_t \sum_{a_{region}} \sum_{c_{region}} AC_{t,a,c} + \sum_t \sum_{t_{in}} \sum_{b_{region}} \sum_{c_{region}} BC_{t,t_{in},b,c}}{\sum_t \sum_a \sum_{c_{region}} AC_{t,a,c} + \sum_t \sum_{t_{in}} \sum_b \sum_{c_{region}} BC_{t,t_{in},b,c}} *100\%$$

In addition, we calculate the weighted average source distance (WASD) traveled by the product. This is a measure commonly used in food system studies to measure localness (Carlsson-Kanyama, 1997; Pirog & Benjamin, 2005). Mathematically,

$$\text{(10)} \qquad \text{WASD} = \frac{\sum_t \sum_a \sum_c AC_{t,a,c} * MileAC_{a,c} + \sum_t \sum_{t_{in}} \sum_b \sum_c BC_{t,t_{in},b,c} * MileBC_{b,c}}{\sum_t \sum_a \sum_c AC_{t,a,c} + \sum_t \sum_{t_{in}} \sum_b \sum_c BC_{t,t_{in},b,c}}$$

4. Results

4.1.Baseline values

The baseline model simulation indicates that total supply chain costs of the cabbage sector in 2012 were about $344 million, of which 80% are production costs, 18% are transportation costs and 2% are storage costs (Table 4). Storage costs happen only in the summer and fall seasons, the latter exhibiting larger magnitude.

Given that consumption is higher in the winter and spring seasons (Table 2), high demand seasons coincide with the lowest supply in cold climate regions. In these seasons, the demand cabbage demand in cold regions is met by supply from warmer regions and from cabbage that is put into storage. This results in higher transportation and storage costs in the winter and spring seasons, as well as higher WASD than annual average. The seasonality of price, as well as regional price difference (which are summarized later in the next section), are both consistent with the 2012 wholesale price reported by USDA.

Insert [Table 4. Baseline results]

Figure 3 shows product flow between supply locations to demand locations on an annual basis. To simplify the figure, the product flow from on-season supply and off-season storage are combined, and only the flows that account for greater than 0.5% of the total flow are shown. Almost 80% of the total cabbage shipped to demand locations are presented in the map and the thickness of the arrow represents the relatively amounts of product shipped to demand locations. California and New York supply the biggest share of total cabbage flow. They supply 13% and 10% of total flow respectively within state.

Insert [Table 4. Figure 3: Baseline flow chart of total supply to demand]

Table 5 presents the marginal land values for supply locations with full production. As mentioned, these marginal values can be viewed as the land value for an additional acre in each supply location in each season. A marginal value equals to zero means that the location-season is below its full production capacity, thereby the total supply chain costs will not be affected if we increase the land acreage in that particular supply location-season.

New York in the fall season has the highest land value ($1,442/acre), followed by northeast and southeast Florida in the spring season ($1,240/acre and $1,143/acre), and Arizona in the spring season ($810/acre). These results are consistent with the estimated yields at each supply location (Table 1), as well as distance to large MSAs. The supply locations-seasons with higher land value generally have higher yields and lower estimated production costs than the average of the U.S.

Insert [Table 5. Baseline marginal value of land under full production]

4.2. Simulation results

-Simulation 1: Increased demand

Using the baseline values, we employ the first simulation scenario- an increased demand among low- and mid-income individuals to reach the national average. As mentioned, the consumption for low and mid-income group is altered to meet the national average per capita consumption. Under this scenario, to account for the storage losses, total domestic production increases around 267 million pounds to meet the additional demand of 247 million pounds. The total supply chain costs increase about 13% to $387 million (Table 6).

Insert [Table 6. Supply chain impacts from simulation scenarios]

Our results indicate that wholesale prices may increase by 38% relative to the baseline scenario. This substantial price increase may incentivize growers to short farmland from other products to cabbage, given the potential increases in revenues associated with higher cabbage prices. Production would continue expanding until the wholesale prices decreases back to the baseline price level. Thus, following simulation 1, to resemble the supply responses, we employ the optimal land expansion scenario (simulation 2).

-*Simulation 2: Increased demand with optimal land acreage expansion*

We employ our optimization model to determine the optimal regions and seasons that can enter into production to avoid that low- and mid-income individuals do not have to pay higher prices for cabbage. Optimality here refers to allocating new acreage to cabbage production based on the marginal value of land at each production location in each season (see section 3.3 for details). Table 7 shows incremental land allocated to cabbage production in cabbage supply locations. New York in the fall season is the most optimal supply location-season for acreage expansion, which we expand the acreage to the 25% limit (1,415 acres) of original land availability.

Table 6, columns 4 and 5, show results for the metrics of interest. Regarding the impacts on supply chain costs, our results, comparing between with and without land expansion, the total supply chain costs decreases from 387 to 378 million dollars. With land expansion, the domestic supply can meet the additional demand more efficiently. The total production quantity is 10 million pounds less, and fewer amounts have to be put into storage.

As the land expansion simulation target at offsetting back to the national average wholesale price, the regional prices differ from the baseline value in the optimal land expansion scenario. The Southwest and West region face slightly higher prices, while other regions are the opposite.

The relatively bigger price drop in Northeast and Southeast might be resulted from the larger land expansion in New York and Florida.

Furthermore, most regions become less self-reliant in the land expansion scenario, except the Northeast. This result shows that if the cabbage supply chain faces a demand shock, the cost-minimizing solution of the model indicates a more nationally-integrated cabbage sector. This is, the supply should move away from localization towards integration at the national level. The gradual increase in WASD is consistent with this result.

Insert [Table 7. Optimal land expansion]

Results from simulations also give us the optimal amount of cabbage shipping to demand locations that reduce the overall supply chain cost. Here, we also combined the on-season supply and off-season storage to demand to simplify the figure. Our maps (Figure 4 and 5) present the changes in movement of cabbage, both increase and decrease from base flow to simulation 1 and simulation 2. To simplify the maps, the largest twenty increases and largest twenty decreases from base flow to simulations are presented. It can be observed from Figure 4 that cabbage movements mostly increase in Southwest and West whereas mostly decrease in Northeast and Southeast. The larger increases in cabbage movements take place within California, Michigan, and New York and the larger decreases in Georgia to Illinois, New York to Michigan, and from Florida to Ohio.

Insert [Figure 4: Change in Cabbage Flow from Base to Simulation 1]

The changes between base and simulation 2 give us a different picture (Figure 5). Here increase and decrease in cabbage flows mostly can be observed in Northeast and Southeast. Larger increases occur from New York and Georgia to different demand locations and larger decreases take place from Texas to Illinois, Ohio to Georgia, and Wisconsin to Texas.

Insert [Figure 5: Change in Cabbage Flow from Base to Simulation 2]

5. Discussion

Our model provides insights of vegetable supply chain impacts on system-wide costs, regional wholesale prices, degree of self-reliance and food miles. Simulating with the differentiated demand increment provides a more accurate scenario for analysis. Comparing to a fixed increment change national-wide, the regional consumption variation is better addressed with the focuses on demographic differences. As most supply chain study emphasizes the production side, this study demonstrates one solution to incorporate regional demography from the demand side.

The results of cost-minimizing production acreage expansion suggest that the supply chain will be toward national-integrated sector rather than localized. Most regions except Northeast have a decrease in self-reliance, and the overall food mile increases. In recent years, increased localization of food supply chains has gotten strong support due to the perceived benefits of stronger local communities, improved environmental stewardship, and higher consumers' preferences (Holloway et al., 2007; Ilbery & Maye, 2005; Winter, 2003). Though we do not consider those social benefits that might be brought from a localized supply chain system, our results suggest the opposite to benefit the system cost-wise.

Having the system-wide cost-minimizing solution is a suitable indication for supply chain impacts in a competitive fresh vegetable market. As wholesale prices can be viewed as the proxy for the retail prices that consumers face, the costs-minimizing solution also points out the supply allocations that would have the smallest negative impacts on consumers in terms of increased prices. When facing a national demand growth, the results provide information for both public and private sectors to understand the possible impacts, such as the regional differences in wholesale prices, resulting from the optimal land reallocation to cabbage production.

Furthermore, the optimal land expansion happens mostly in New York and Florida's supply locations. New York state has one of the highest yield at 428 hundred-pound per acre, while Florida has relatively lower yields at 328 hundred-pound per acre. To meet the additional demand, land acreage expansion in these two states can best minimize the system-wide costs. As our model takes regional differences in input costs, distance to consumer, and other factors into account, these results provide actionable information for the industry to identify the relative value of production sites.

6. Conclusion

We employ a spatially disaggregated transshipment model of the U.S cabbage sector to analyze the impacts of an income-based demand increment shock on the structure and performance of the supply chain. This is a relevant research question since there are a number of programs and initiatives aiming at promoting higher vegetable consumption to lower income households to in the U.S. We have differentiated the demand increment by income groups to address the potential demand growth for dark green vegetables accurately. The mathematical programming model determines the optimal level of production and storage, and the product flow (shipments of cabbage from supply locations to demand locations) as which minimize the total supply chain costs. While the product flow is constrained by the production capacity and shrinkage resulting from storing cabbage, total shipments from supply and storage locations have to meet consumer demand in each demand location in each season. Our model is spatially disaggregated and takes into account seasonality in both production and consumption.

By using the U.S cabbage as an example for dark greens, we have illustrated how a growing demand influences the national supply chain for the product, including costs, wholesale prices, and the extent of localization of food systems (e.g., the degree of self-reliance, the average distance traveled by the product, etc.). This model also provides information on the cost-minimizing acreage expansion for meeting the additional demand, as well as informs the resulting changes on the national supply chain. These results can shed light on the sophisticated vegetable supply chain structure and provide domestic industry the relative value of production sites.

While our analysis provides valuable insights on the impacts of demand-side shocks on vegetable supply chain, this model can be used to employ other relevant issues in the vegetable supply chain. For example, the produce industry can examine the supply chain reactions if introducing new crop varieties that do not follow the typical production season. Or if certain production sites would like to expand and develop a more localized supply chain system, our model can be adapted to assess the impacts of localization in various performance dimensions, such as the changes in average distances traveled by the product, which are important to understand environmental benefits of food system localization.

Lastly, there are limitations that should be addressed in future research. First, our study assumes perfectly competitive markets and cost minimizing behavior of firms participating in the cabbage supply chain. This assumption should be validated by developing statistical tests based on time-series analysis to test for market integration and imperfect competition. Second, although we did impose a 25% acreage expansion limit in the simulation, the opportunity costs of shifting land into cabbage production from other high-value crops are yet to be taken into account. Third, our model omits the case of processed cabbage. While, in reality, the markets for fresh and processed cabbage are interconnected and both affect grower production decisions. Although the processed cabbage has only a small share of the market, the analysis can be extended to incorporate processed cabbage in the future.

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