A decade later: Changes in the economic and environmental outcomes of food system regionalization, 2007-2017: Broccoli in the eastern United States

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Abstract

Local and regional food systems play an important role in agricultural sector in the United States. Governments and the private sector are increasing their support for local and regional systems as vehicles for community and economic development, and as a means for economic, environmental, and social sustainability. With growing consumer interest and efforts from public and private sectors toward food localization, local and regional food systems in the United States have expanded quickly over the past decade. Despite this rapid growth, the economic and environmental effects are not well understood. In this paper, we employ a spatial-temporal model of production and transportation to evaluate the economic and environmental outcomes of a decade-year long process of food regionalization for fresh broccoli in the United States. The total broccoli acreage in the U.S. eastern region increased by 60% from 2007 to 2017. Results indicate that eastern broccoli supply chains have the potential to meet over 15% of the annual demand in eastern markets with modestly increased supply-chain costs and shortened food miles as of 2017. Food miles from mainstream supply locations to eastern markets increased in 2017, while miles travelled from eastern supply region to eastern markets decreased over 30%. The eastern broccoli system in 2017 had lower supply-chain costs per box than the mainstream broccoli system.

Introduction

Local and regional food systems become a major pillar of agriculture and rural economic development in the United States (USDA, 2015). Growing consumer interest in buying locally produced products creates new market opportunities for American farmers, ranchers, and food businesses (USDA, 2016). These new crop markets and opportunities help building alternative food systems: local and regional food supply systems. Increasingly, government and private sector are supporting local and regional systems as vehicles for community and economic development, and as a means for potential economic, environmental and social sustainability (e.g., Peters et al., 2009; Harris et al., 2016; Mullinix et al., 2016; Kissinger et al., 2019). With growing consumer interest and efforts from public and private sectors toward the food localization, local and regional food systems in the United States are quickly expanding over the past decade. Between 2009 and 2015, the USDA invested over $1 billion in more than 40,000 local and regional food system projects (USDA, 2016). Food policies in the United States have also met the needs generated by ongoing shifts in consumer preferences towards local and regional foods and have supported the expansion of regional food systems (Johnson and Tadlock, 2019).

Despite the development of local and regional food systems in the last decade, the economic and environmental effects of their growth is not well understood. Existing studies analyze the economic and environmental impacts of increasing food localization (e.g., Nicholson et al., 2011; Atallah et al., 2014). These potential localization or regionalization outcomes vary among food commodities. For example, increasing localization of fluid milk would increase its overall supply-chain costs and total distances fluid milk traveled (food miles) (Nicholson et al., 2011). In the case of fresh broccoli, however, food localization may reduce total supply-chain costs and food miles (Atallah et al., 2014). These studies provide thorough potential impacts of expanding the alternative food systems and increasing local food supply; however, policy makers and stakeholders have little evidence on the ex-post economic and environmental outcomes of localization and regionalization. Localization impacts might differ from ex-ante food localization outcomes simulated using models assuming that production costs, transportation costs, and demand do not change during the period when acreage expansion happens. In reality, while food system regionalization and expansion take place, production costs, trucking rates and demand for food products change over time.

Our results inform food policies that support and invest in regional food systems on their actual impacts and evolution, which are important feedback to help build a decentralized supply chain. Current and potential grower-packer-shippers might also be interested in information about the optimal magnitude, locations and seasonality of product flows. Our results are relevant for fresh produce growers and other stakeholders, as they can benefit from information about economic and environmental impacts of regional food systems to guide investment decisions, since the growth of regional food systems would also influence supply-chain costs and market shares.

Tracking the evolution of regional food systems would also support more private and public discussions regarding the comparative analysis of conventional vs. regional food systems. The debate over the past two decades about the conventional and regional food systems remains unsolved (e.g., Bellows and Hamm, 2001; Peters et al., 2009; Shindelar and Michel, 2015), and some have challenged the potential benefits of food system localization and the assumption that local and regional food systems are more sustainable than their conventional counterparts (e.g., Bellows and Hamm, 2001; Kissinger et al., 2019). Food system researchers have called for more comprehensive comparative analysis of existing and desired food systems to improve sustainability (e.g., Kissinger et al., 2019).

Fresh broccoli is an excellent case for assessing the evolution of a regional food system in the United States. The mainstream broccoli suppliers, California and Arizona, account for over 90 percent fresh broccoli in the United States (AgMRC, 2018), but there are concerns about long-term water availability to support water-intensive crops such as broccoli in this region. Meanwhile, A regional broccoli supply system emerged in the eastern areas of the U.S. since the development of new varieties that are suitable for production along the Eastern Seaboard (Atallah et al., 2014). The total broccoli acreage in the U.S. eastern region increased by 60% (Table 1) from 2007 to 2017 (USDA NASS, 2008; USDA NASS, 2019). The acres planted in the western U.S. have only increased by 0.52% (Table 1) during the same time. The quickly expanding eastern U.S. broccoli system provides a good opportunity to examine the evolution of a regional food system over a decade. Moreover, methods and lessons from studying broccoli could be generalizable to other fresh crops, which are mainly produced in the Western U.S. but mostly consumed in large metropolitan areas in the Eastern U.S. (US Census, 2010).

[Insert Table 1 here]

In this paper, we employ a spatial-temporal model of production and transportation to evaluate and compare the economic and environmental outcomes of a decade-long process of food regionalization for fresh broccoli in the United States. The spatial-temporal model depicts the production and transportation of fresh broccoli in the U.S. We calibrate the model using both primary and secondary data for the United States in 2007 and 2017. We solve for the cost-minimizing production levels in each location and season, and transport patterns between supply and demand locations, for each season. We measure the changes in supply-chain costs and food miles by season for the mainstream broccoli system and the eastern broccoli system. We then measure the changes in the share of eastern-grown broccoli in the U.S. eastern markets and report seasonal eastern broccoli supply chain flows.

This study is organized as follows. After this introduction, we discuss the literature on local and regional food systems, emphasizing the links to its expansion and potential economic impacts. Next, we describe our model of U.S. broccoli supply chains. In turn, we present our results and discuss the policy implications. The last section offers concluding remarks, discusses limitations of our study and proposes topics for future research.

2. Literature review

With the quick expansion of local and regional food systems over the past decade, the research evaluating new, alternative food systems is substantially growing. Food system researchers studied and predicted the economic, environmental, and social impacts of increasing regional food systems (e.g., Nicholson et al., 2011; Atallah et al., 2014; Christensen and O'Sullivan, 2015). One significant challenge or barrier of local and regional food systems is the cost of localized food (Mittal et al., 2018). Often, production costs in new production regions can be higher than in mainstream production regions (Atallah and Gómez, 2013). Many farmers struggle to afford the high marketing and transportation costs associated with distributing their products (e.g., Low et al., 2015). High supply-chain costs might discourage local farmers to enter production and therefore might impede the expansion of food regionalization. Moreover, many of the effects of localization depend on the food item under study and the structure of its supply chain, limiting the ability of researchers to draw general conclusions. Atallah et al. (2014) showed that increasing food localization may reduce broccoli supply-chain costs and the average distance travelled by the product from farm to demand locations. In contrast, Nicholson et al. (2015) found that the localization of dairy supply chains increases the total distance traveled by fluid milk and overall supply-chain costs. In addition, because of the lack of ex-post studies, the actual changes in supply-chain costs of localized and regionalized foods over the past decade remain unknown.

Ten years ago, all food localization projects were experimental, and a small percentage of growers and consumers were interested in marketing or growing local produce (Feenstra, 2011). Localization was underway and ex-ante analyzes were justified. A decade later, much localization occurred but few ex-post studies exist. In particular, we do not know how the market share of localized foods has changed over the past decade. The share of local and regional foods in regional markets is an important indicator of development of regional food systems and it varies among commodities. Clancy et al. (2017) found that apples, cabbage, milk and potatoes are more self-reliant in the northeast region in 2015 than other products such as frozen broccoli, bread, beef, and canned potatoes. However, little is known how regional self-reliance for those high-value produces has evolved with increasing investments and supports on local and regional food system from public and private sectors.

Research has focused on evaluating multidimensional impacts (i.e., economic, environmental and social) of different food supply systems. Brodt et al. (2013) showed that conventionally produced tomatoes are almost equivalent in energy use and GHG emissions but use significantly more water resources relative to their regionally grown counterparts. Similarly, Kissinger et al. (2019) challenged the idea that local food systems are necessarily more environmentally sustainable than the conventional ones. Besides comparing environmental outcomes, Grivins et al. (2016) compared the social performance of global and local berry supply chains and showed that global berry supply chains performed better than local supply chains according to social indicators such as wage level and civic responsibility. Results from comparing the mainstream and local food systems differ across commodities and the perspective of impacts.

Optimization models are advantageous to assess food supply chains and identify optimal decisions regarding production patterns and supply chain designs (e.g., Flores and Villalobos, 2018; Mardani et al., 2019). More importantly, this standardized methodology allows replication for other commodities and could address the seasonal and spatial components of food supply chains when evaluating increasingly complex regional food systems (e.g., Atallah et al., 2014; Christensen and Rita, 2015). In this paper, we employ a production-transportation model of U.S. fresh broccoli industry and calibrated it to year 2007 and 2017 in order to assess the evolution of a regional food system regarding its economic and environmental outcomes over a ten-year period, that is, before and after the system has developed.

3. Methods

Production and transportation model

We employ a spatial-temporal optimization model of production and transportation to compare the economic and environmental outcomes of the U.S. eastern broccoli system in 2007 and 2017. This production-transportation model allows us to analyze the resulting spatial and seasonal changes in the U.S. broccoli supply chains, which have two major characteristics: (1) fresh broccoli is perishable and seasonal, and (2) though fresh broccoli is consumed nationally, 92% of it is produced in California (AgMRC, 2018). We parameterize the model with 2007 and 2017 data to solve for the production and transportation patterns that minimize total production and transportation costs in these years. Then, we comparatively analyze the supply-chain costs, market share and weighted average source distance (WASD) for the eastern broccoli system and conventional system for these two years and compare the eastern supply chain flows in 2007 and 2017 for each season.

Broccoli supply, demand, and transportation data

To utilize the production and transportation model we incorporate supply, demand, and transportation data. Data pertaining to supply include yield, unit production cost, and seasonal land available for broccoli production at each supply location. Data pertaining to demand include seasonal volumes demanded at each supply location. Data pertaining to transportation include distances between supply location and demand market, and seasonal unit transportation costs at each supply locations.

Modelled supply locations include ten fresh broccoli production regions in the eastern U.S., two western U.S. mainstream producing regions (California and Arizona), and imports from Mexico and Canada for a total of 14 broccoli supply regions. The fresh broccoli production regions in the eastern U.S. are Maine, New York, Pennsylvania, Virginia, North Carolina, South Carolina, Georgia, New Jersey, Maryland, and Florida. We employ production cost estimates and yields in 2007 from existing regional broccoli crop budget (Atallah and Gómez, 2013). We use updated yield estimates and production costs in 2017, where production costs are adjusted by the change in labor wages between 2007 and 2017 in each supply location (US census, 2011; DOL, 2021). We use regional broccoli acreage estimates (USDA NASS, 2008; USDA NASS, 2019) and confirm them with estimates from the Eastern Broccoli Project (citation or website).

[Insert Table 2 here]

The model has 33 demand nodes. We use the large metropolitan statistical areas (MSAs) to define demand locations in the eastern U.S. Demand is allocated to MSAs and the state geographic centers based on population levels (US Census, 2020) and USDA's per capital disappearance for fresh broccoli in both 2007 and 2017 (USDA ERS, 2020). Supply and demand quantities are measured in 21-lb broccoli boxes. For distances between production locations and demand nodes, we use the U.S. state spatial distance matric in Yu (2007). We use USDA's quarterly agricultural refrigerated trucking rates (USDA, 2007; USDA, 2017) and distances between supply locations to demand sites to calculate seasonal transportation cost for each supply location. To calculate shipment costs from Mexico, we use data from the Mexico Transport Cost Indicator Report (USDA, 2013; USDA, 2017) and assumed the entry port is Pharr, Texas.

Model formulation

We followed the integrated production-transportation model employed in Atallah et al. (2014) and solved twice for optimal fresh broccoli production level and transport patterns in 2007 and 2017 respectively, using each year's corresponding data. The model is structured as a mixed integer linear programming problem as follows:

$$\text{Minimize } \sum_i^I \sum_k^K PCOST_i * XP_{i,k} + \sum_i^I \sum_j^J \sum_k^K TCOST_{i,j,k} * DIS_{i,j} * XT_{i,j,k} \quad (1)$$

$$\text{Subject to: } \sum_j^J XT_{i,j,k} \leq XP_{i,k} \quad (2)$$

$$\sum_i^I XT_{i,j,k} \geq DEMAND_{j,k} \quad (3)$$

$$\frac{XP_{i,k}}{YIELD_i} \leq LAND_{i,k} \quad (4)$$

The objective function (1) here is to minimize total supply chain costs, which include total production costs for all supply locations and total transportation costs from all origins to demand locations. The model solves for two decision variables, $XP_{i,k}$ and $XT_{i,j,k}$, where $XP_{i,k}$ is the optimal production level at supply location *i* in season *k* and $XT_{i,j,k}$ is the optimal quantities transported from supply location *i* to demand location *j* in season *k*. $PCOST_i$ is the average total unit production cost ($/box) in each supply location *i* and $TCOST_{i,j,k}$ is the average total unit transportation cost ($/mile/box) from supply location *i* to demand location *j* in season *k*. $DIS_{i,j}$ (miles) is the distance between supply location *i* to demand location *j*.

In order for the production and transport patterns to be feasible, they must simultaneously satisfy three constraints: (1) broccoli shipped from supply location *i* to all demand locations *j* in season *k* cannot exceed production level at supply *i* in season *k* (Equation 2); (2) broccoli shipped to demand location *j* in season *k* from all supply locations *i* have to at least satisfy the demand level ($DEMAND_{j,k}$) at each demand location *j* in season *k* (Equation 3) ; (3) land ($LAND_{i,k}$) used to produce broccoli should not exceed the available land at supply location *i* in season *k*, where $YIELD_i$ is the supply location 's average broccoli yield (Equation 4).

We use the weighted average source distance (WASD), or food miles, a measure commonly used in food system studies (Coley et al., 2009) to calculate a single distance figure that combines information on the distances from producers to consumers and the amount of product transported. We calculate eastern grown WASD (*EWASD*), mainstream sourced WASD (*MWASD*), and national WASD (*NWASD*) using the definitions in Equations 5, 6, and 7. The calculations allow for the comparison of the food miles for two different broccoli system (eastern system and mainstream system) in eastern markets and to understand their changes from 2007 to 2017.

$$EWASD = \frac{\sum_i^{EORIG}\sum_j^{EDEST}\sum_k^{SEAS} DIS_{i,j}*XT_{i,j,k}}{\sum_i^{EORIG}\sum_j^{EDEST}\sum_k^{SEAS} XT_{i,j,k}} \quad (5)$$

$$MWASD = \frac{\sum_i^{MORIG}\sum_j^{EDEST}\sum_k^{SEAS} DIS_{i,j}*XT_{i,j,k}}{\sum_i^{MORIG}\sum_j^{EDEST}\sum_k^{SEAS} XT_{i,j,k}} \quad (6)$$

$$NWASD = \frac{\sum_i^{ORIG}\sum_j^{EDEST}\sum_k^{SEAS} DIS_{i,j}*XT_{i,j,k}}{\sum_i^{ORIG}\sum_j^{EDEST}\sum_k^{SEAS} XT_{i,j,k}} \quad (7)$$

EWASD is the average distance from eastern growers to eastern markets. *MWASD* is defined as the average distance from mainstream (non-eastern) growers, including California, Arizona, Mexico and Canada, to eastern markets. *NWASD* represents the average distance from all broccoli growers and imports to eastern markets. We also measure how the share of eastern-produced broccoli and transported quantities in eastern markets change seasonally and annually in 2007 and 2017. We calculate the share of eastern-grown broccoli in east coast markets as follows:

$$Eshare = \frac{\sum_{e}^{EORIG} \sum_{f}^{EDEST} \sum_{k}^{SEAS} XT_{i,j,k}}{\sum_{i}^{ORIG} \sum_{j}^{EDEST} \sum_{k}^{SEAS} XT_{i,j,k}} \tag{8}$$

4. Results

Using the production levels and transportation patterns from the years before and after localization occurred (2007 and 2017), we calculate the market share of eastern-grown broccoli in eastern markets, supply chain costs and food miles for the mainstream-sourced and eastern-grown broccoli in eastern markets, and report the seasonal eastern supply chain flows for 2007 and 2017. The results indicate that the annual average market share of eastern-grown broccoli in U.S. eastern markets (Eshare) increased from 12% in 2007 to 15% in 2017 (Table 4). Regarding supply-chain costs and food miles, our results are not consistent with previous research (Atallah et al., 2014) which predicted that increasing localization of fresh broccoli would decrease total supply-chain costs and food miles in eastern markets. Our results show that supply-chain costs increase for both mainstream-sourced and eastern-grown broccoli, and food miles increase as well in 2017 compared with 2007 in eastern markets. The difference comes from the assumption regarding production costs, transportation costs, demand and available land in the West Coast in Atallah et al. (2014). Atallah et al. (2014) assumed that all these parameter values are fixed when broccoli acreage increases. In our study, however, these parameters changed in 2017 compared with 2007. Our results also show that in 2017, the eastern-grown broccoli had lower unit supply-chain costs and food miles than the mainstream-sourced broccoli in eastern markets than 2007.

4.1 Evolution of regionalization: changes in the supply-chain costs

The results indicate that the annual supply-chain costs ($/box) of eastern-grown broccoli are higher than the mainstream-sourced broccoli costs in 2007 (Table 3). However, in 2007, the supply-chain costs of eastern-grown broccoli modestly increase, and are lower than the mainstream ones (Table 4). The supply-chain cost in 2007 and 2017 for eastern-grown broccoli was $13.90/box and $14.37/box respectively. Broccoli sourced in mainstream locations in 2007 and 2017 cost $13.36/box and $15.57/box respectively. The results indicate the cost of a 21-lb box of broccoli sourced in the eastern supply chain in 2017 is $1.20 less than an equivalent box sourced elsewhere. The annual supply-chain costs of mainstream sourced broccoli increased 17% in 2017, while the eastern-grown broccoli only increased 3% (Table 3). The average supply-chain costs of fresh broccoli in eastern markets, which combines broccoli from all eastern region states and mainstream regions (West Coast and imports), increased by 14% in 2017 (Table 3) with a 60% increase of eastern broccoli acreage (Table1). The results regarding supply-chain costs meet our expectation since parameters including unit production costs and transportation costs both increased in 2017, even though the changes are different with the results in Atallah et al. (2014). Atallah et al. (2014) assumed these costs constant in their acreage increase scenarios and projected that the total supply chain costs would decrease by 1% when the eastern broccoli acreage increase by 30% and decrease by 2% when the broccoli acreage increase by 100%.

[Insert Table 3 here]

4.2 Evolution of regionalization: changes in the share of eastern-grown broccoli in eastern markets

Atallah et al. (2014) predicted that the market share of eastern-grown broccoli in eastern markets would increase by 6% when the eastern broccoli acreage increases by 30%, and by 18% when the eastern broccoli acreage increases by 100%. In our results, the seasonal share of eastern-grown broccoli increased, but in smaller (percentage point) magnitudes as in Atallah et al. (2014). Our results show that with a 60% actual increase of broccoli acreage in eastern regions, annual share of eastern-grown broccoli in eastern markets increased from 12% in 2007 to 15% in 2017 (Table 4). In spring and winter, the share of eastern-grown broccoli increases by about 7% (Table 4). For the summer and fall seasons, market share of eastern-grown broccoli decreases slightly (Table 4). The amount of broccoli shipped from eastern suppliers to eastern markets increased substantially over the ten years. The largest change was in the seasons where the market share increased (spring and winter). Winter shipments were up by 435% and spring shipments were up 232% (Table 4). Shipments within the eastern regions increased even in the seasons in which market share declined. Summer shipments were up by 21% and fall shipments were up 14% (Table 4).

[Insert Table 4 here]

4.3 Evolution of regionalization: changes in eastern broccoli supply chain flows

Expansion of local and regional food systems is associated with the spatial reorganization of broccoli supply chain configurations within the eastern U.S. as well as nationally. Figures 1, 2, 3, and 4 describe seasonal eastern broccoli supply chain flows in 2007 and 2017. Our model's 2007 results show that optimal broccoli supply locations should not include Georgia (Figure 1, 3 and 4). This is because the broccoli unit production cost in Georgia is the highest among all broccoli supply locations in our 2007 model and the yield is low compared to that in other supply locations. However, in 2017, the results regarding optimal supply locations include Georgia. In 2017, the difference of unit production cost between Georgia and all other states became much small so that Georgia can supply large MSAs at a relatively low cost.

Eastern broccoli supply chain flows in spring 2007 and 2017

According to the model, supply chain flows from eastern supply locations to eastern markets increases are larger in spring 2017 than in 2007 (Figure 1). In spring 2007, 100% of broccoli shipped to Charlotte, NC were from mainstream supply locations (Table 5). In contrast, in 2017 32% broccoli shipped to Charlotte, NC came from eastern region states (Table 5). Charleston, SC saw a dramatic shift in broccoli sourcing. In spring 2007 100% of the broccoli shipped to Charleston, SC was sourced from mainstream locations. By spring 2017, 100% of the broccoli shipped to the city was sourced from eastern states. Similar shifts in sourcing occurred in Augusta, GA and Gainesville, FL. In 2007 both cities relied on mainstream supply for 100% of their broccoli supply, but by spring 2017 Augusta, GA was sourcing 64% of its broccoli from eastern states while Gainesville, FL was sourcing 19% from eastern states.

[Insert Table 5 here]

[Insert Figure 1 here]

Eastern broccoli supply chain flows in summer 2007 and 2017

The basic supply chain structures in summer 2007 and 2017 saw minor changes (Figure 2). Atallah et al. (2014) predicted that flow reorganization happens in New York City under all eastern acreage increase scenarios. By contrast, Table 5 illustrates that no spatial reorganization occurs in broccoli flows into New York City when eastern acreage increases, and the share of eastern broccoli in New York City has not changed substantially in 2017 relative to 2007. Table 5 shows that in 2007, 65% of total broccoli shipped to Buffalo, NY was from mainstream regions, and the remaining 35% sourced from eastern states. In 2017 Buffalo, NY sourced 48% of its broccoli from eastern states, an increase of 12% over the ten-year period. Conversely, both Bridgeport, CT (CT1) and Hartford, CT (CT2) sourced 100% broccoli from eastern supply regions during the summer in 2007. However, by 2017, Bridgeport, CT (CT1) increased its mainstream sourcing resulting in 52% of broccoli shipped to the area being produced in mainstream regions while Hartford, CT (CT2) saw 9% of its broccoli being sourced from mainstream regions in the summer. CT1 and CT2 get their eastern-grown broccoli from Maine state in both two years. However, in 2017, Maine got allocated more broccoli to other MSAs (MA 1, MA2, MA3, ME), with a shorter distance origin, leaving CT1 and CT2 with no other option than sourcing from mainstream origins. Flow reorganization results in CT1 and CT2 illustrate cases where increased regionalization counterintuitively leads to a decrease in regional product flows.

[Insert Figure 2 here]

Eastern broccoli supply chain flows in fall 2007 and 2017

In 2017, Georgia enters as an additional optimal supply location in the Eastern Coasts, which substantially contributed to the increase in the total supply chain flows in eastern regions in 2017. Other increases in fall eastern supply flows are caused by increases in production in New York, North Carolina, and South Carolina. In 2007, all broccoli shipped to Albany, NY (NY2), Charlotte, NC (NC1), Charleston, SC (SC3) and Gainesville, FL (FL3) in the fall is from mainstream supply locations. By 2017 these four regions shifted to sourcing a majority of their broccoli from eastern states. For example, 62% of total broccoli supply in NY2 was from the eastern region in 2017 while in 2007 100% was sourced from mainstream locations (Table 5). In contrast, in New York city (NY3) and Durham, NC (NC2), the shares of eastern-grown broccoli decreased by 2017 resulting in over 50% of supplied broccoli to both cities coming from mainstream regions during the fall. Maine was the main broccoli supplier in eastern states for NY3 in 2007, however, Maine got allocated to more broccoli to other MSAs, which are closer to Maine than NY3. For NC2, over 60% of supplied broccoli came from California in 2017, instead of its dominant supplier North Carolina and Virginia in 2007 (91% broccoli sourced from these two eastern states. The potential reason is the production costs in North Carolina and Virginia are higher than California, even NC2 is much closer to North Carolina and Virginia than California.

[Insert Figure 3 here]

Eastern broccoli supply chain flows in winter 2007 and 2017

In winter 2017, the broccoli supply locations expanded to include Georgia in addition to Florida (Figure 4). Figure 4 also shows Georgia supply coming from southern Georgia in Winter 2017. Results indicate broccoli quantities shipped from eastern regions to eastern markets also increased by 2017, compared to 2007. In 2007, 100% of broccoli demand in Augusta, GA and Deltona, FL was satisfied by mainstream regions (Table 5). By 2017, eastern-grown broccoli had grown to provide 58% of broccoli in Augusta (GA2) and 79% in Deltona (FL2).

[Insert Figure 4 here]

4.4 Evolution of regionalization: changes in food miles

The eastern supply meets the expectation that a local or regional supply travels less than that from outside the region. Since the largest eastern supply areas in Maine and Florida are 1600 miles apart, the within-region distances can be quite large. Still, this distance is smaller than the one that separates Atlanta, GA and Salinas, CA (around 2,400 miles) or the one that separates it from Guanajuato, Mexico (around 1,650 miles). Atlanta, GA, as an example of a smaller market and long distances from the west coasts, makes a strong case that the actual difference in food miles need to be quantified. The annual average distance travelled from eastern broccoli growers to eastern markets (365 miles) was far less than that from the out-of-region supply (2,533 miles; Table 6). The annual average distance from eastern broccoli regions to eastern markets decreased by 30%, from 365 miles in 2007 to 255 miles in 2017 (Table 6). This decrease is due to the reorganization product flows whereby eastern produced broccoli substituted some of the mainstream produced broccoli in eastern states. In contrast, the annual average distance of broccoli produced in mainstream source locations increased by 11%, from 2,533 miles in 2007 to 2,817 miles in 2017. This increase is because California is still a dominant supplier for broccoli in the eastern states, with lower production costs and transportation cost in 2017.

[Insert Table 6 here]

5. Discussion

The model solutions provide several insights regarding how the regionalization of a supply evolves over ten year and impacts of this regionalization on supply chain costs, market share, product flows and food miles. First, the model results show that eastern broccoli supply chains have the potential to meet over 15% of the annual demand of eastern markets with modestly increased supply-chain costs. Despite eastern states having limited land with an appropriate climate to produce broccoli in spring and winter, market shares of eastern grown broccoli in these two seasons have increased by more than 6% from 2007 to 2017. One important advantage of sourcing eastern grown broccoli is the lower supply chain cost compared to the broccoli sourced from the mainstream system in 2017. Supply-chain costs of mainstream-sourced broccoli are likely to rise due to expensive rent and limited irrigation water in western production regions where irrigation water can be subject to rationing in times of drought.

Second, the regional food supply chains became shorter in 2017 compared with 2007, and its structure changed depending on demand sites and seasons. Not surprisingly, the average distance travelled from mainstream supply sites including the West Coast, Mexico, and Canada to eastern markets is much high, about 11 times as far (2817 miles in 2017) as the distance travelled from eastern growers. Thousands of miles could produce massive carbon emission and pollution. Moreover, some of supply chain flows in the eastern broccoli system changed unexpectedly. Changes in the share of eastern sourced broccoli and mainstream sourced broccoli supply for eastern demand nodes differs a lot, depending on the locations to which broccoli is transported. The optimal supply chain structure we identified in this paper might provide insights for local and regional policies when designing their desired network.

This work provides insight on the relationship between the mainstream and regional food systems. Our results demonstrate that the regional broccoli system has become integral to the entire national broccoli supply system by complementing the mainstream system. Using cost minimization as the goal, the optimal modeled solution includes both mainstream and eastern supply systems working together to meet market demand. Discussions and future work for the mainstream and regional food systems should focus on how to leverage each of their attributes and advantages to maximize their contributions for the national supply. Policy makers should consider the impacts on the mainstream food system when designing policies to expand local and regional food systems. Our results also show the eastern broccoli system has lower supply-chain costs and food miles, which are likely to add up and become significant over time. As the dominant supply, the mainstream broccoli system still holds high national market shares with lower unit production costs.

The optimal solution from our model for 2017 shows that Arizona should not transport broccoli to eastern markets in 2017 and instead Georgia should produce more to satisfy eastern demand while minimizing the total production and transportation costs. The solutions might provide insights for structuring the future optimal supply system by giving the optimal magnitude, locations and seasons. However, since the food system is more complicated than this model, outcomes such as social and environmental effects should be measured to assess its performance and sustainability.

6. Conclusions

In this paper we employed a spatial-temporal transshipment model of the U.S. broccoli industry to analyze the actual changes and evolution regarding economic and environmental outcomes for a regional food system from 2007 to 2017. The primary conclusion is that the eastern broccoli system performed as expected after 10 years, with increased market share and supply-chain cost advantage and distance advantage. Increased localization modestly increases the total supply chain costs, but the cost advantage of local food system gradually appears over time compared to the mainstream-sourced produce. The positive trend and increasing market size also present opportunities for existing and potential farmers and food businesses to expand regional food production. Although the model is used to assess the U.S. eastern broccoli systems, we believe that our model is generalizable and can be adopted to evaluate and track other regional food systems, especially those involving fresh produce largely produced in few regions but consumed nationally.

The decade-long economic and environmental effects of food system regionalization with detailed supply chain structures provide insights into the optimal planning and design of local and regional supply system for policy makers and other stakeholders. Product flow reorganizations occur differently for each season and large metropolitan areas in the Eastern U.S. Regional supply structure of eastern broccoli system shows small changes in summer and fall seasons, while major flow reorganizations occur in spring and winter seasons. Therefore, grower-shipper-packer and policy makers should consider increased localization impacts of fresh produce supply chains by their segment, season and location in order to appreciate the different impacts within the region.

Our findings are valuable to the fresh vegetable industry (grower-packer-shipper), policy makers and other stakeholders interested in localization and regional food system. Nonetheless, our model has several limitations that deserve further investigation. First, the fresh vegetables supply chain might be influenced by several supply disruptions, such as the water crisis in western U.S. Long-lasting droughts are driving the water shortages across much of the west and are likely to reduce crop yields (Dinar et al., 2019), lead farmers to plant fewer acres and increase production costs such as irrigation water, or to reduce acreage or abandon production altogether (Goldhamer and Fereres, 2017). The spatial-temporal model can be expanded to include or evaluate the impacts of supply disruptions on the regional food system. Such changes might limit, or increase the production cost, of broccoli in California and Arizona. Food system researchers can use the transshipment model to identify the optimal eastern supply locations to meet national demand while minimizing the total production and transportation costs. Second, we assumed that broccoli acreage increases in the eastern states are a small fraction of total fresh vegetable acreages. Future research can include the crops that compete with broccoli for land in each eastern state and their opportunity costs of broccoli acreage expansion in the model. In sum, these limitations highlight the need to for adding important supply shocks and opportunity costs in the model to complement the study.

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Table 1

Estimated U.S. Broccoli acreage from 2007 to 2017.

Location	Acres in 2007	2017	
		Acres	%Change
Maine	5,205	5,948	14.27%
New York	400	634	58.50%
Penn	183	947	417.49%
Virginia	551	411	-25.41%
North Carolina	187	590	215.51%
South Carolina	750	886	18.13%
Georgia	219	316	44.29%
Florida	600	3,000	400.00%
New Jersey	139	489	251.80%
Maryland	35	34	-2.86%
Total Eastern	8,269	13,255	60.30%
California	106,271	109,423	2.97%
Arizona	11,869	9,329	-21.40%
Total western	118,140	118,752	0.52%

Source: Estimates from Eastern broccoli project director and USDA-NASS census of Agricultural in 2007 and 2017.

Table 2

Estimated U.S. Broccoli import from Mexico and Canada in 2007 and 2017.

	2007	2017	Change	% Change
Import (1,000 boxes)				
Mexico				
Spring	1,672	7,056	5,385	322.06%
Summer	763	3,211	2,448	320.72%
Fall	2,209	4,748	2,538	114.89%
Winter	3,579	7,510	3,930	109.81%
Annual	8,224	22,525	14,301	173.90%
Canada				
Spring	112	179	66	59.10%
Summer	51	81	30	58.59%
Fall	148	120	-28	-19.00%
Winter	240	190	-50	-20.91%
Annual	552	570	18	3.25%

Source: Estimates from USDA-ERS Data by Commodity-Imports and Exports in 2007 and 2017.

Table 3

Changes on supply-chain costs in U.S. eastern markets.

	2007	2017	Change	% Change
Supply-chain costs ($/box)				
Average supply-chain costs of all sourced broccoli				
Spring	14.22	15.19	0.97	6.82%
Summer	14.32	15.69	1.37	9.54%
Fall	13.00	15.53	2.53	19.44%
Winter	12.26	15.16	2.90	23.66%
Annual	13.45	15.39	1.94	14.39%
Supply-chain costs of eastern-grown broccoli				
Spring	13.35	13.66	0.31	2.35%
Summer	14.02	14.81	0.79	5.66%
Fall	14.06	14.88	0.83	5.87%
Winter	11.99	13.06	1.07	8.91%
Annual	13.90	14.37	0.48	3.42%
Supply-chain costs of mainstream sourced broccoli				
Spring	14.14	15.37	1.23	8.72%
Summer	14.39	15.86	1.47	10.23%
Fall	12.57	15.75	3.18	25.32%
Winter	12.27	15.36	3.10	25.23%
Annual	13.36	15.57	2.21	16.55%

Source: Authors' calculations based on the optimization models.

Table 4

Changes on share of eastern-grown broccoli and transported eastern-grown broccoli quantities and mainstream sourced broccoli quantities in U.S. eastern markets.

	2007	2017	Change	% Change
Market share of eastern-grown broccoli (%)				
Spring	4.00	10.53	6.53	n/a
Summer	16.36	15.73	-0.63	n/a
Fall	28.87	26.03	-2.84	n/a
Winter	2.05	8.70	6.65	n/a
Annual	12.48	15.02	2.54	n/a
Transported eastern-grown broccoli quantities (1,000 boxes)				
Spring	306	1,016	710	232.41%
Summer	1,237	1,500	264	21.32%
Fall	2,041	2,323	282	13.81%
Winter	158	847	689	435.00%
Annual	3,741	5,686	1,945	51.99%
Transported mainstream sourced broccoli quantities (1,000 boxes)				
Spring	306	1,016	710	232.41%
Summer	1,237	1,500	264	21.32%
Fall	2,041	2,323	282	13.81%
Winter	158	847	689	435.00%
Annual	3,741	5,686	1,945	51.99%

Source: Authors' calculations based on the optimization models.

Table 5

Changes on seasonal broccoli flows (1000 boxes) from eastern locations and mainstream locations to eastern markets in 2007 and 2017. (Percentage of total supply in the parentheses)

	2007		2017	
Demand locations	Eastern supply	mainstream supply	Eastern supply	mainstream supply
Spring				
Charlotte, North Carolina[1]	0 (0.00%)	246 (100.00%)	104 (31.91%)	222 (68.09%)
Charleston, South Carolina[2]	0 (0.00%)	84 (100.00%)	120 (100.00%)	0 (0.00%)
Augusta, Georgia[3]	0 (0.00%)	73 (100.00%)	61 (63.95%)	34 (36.05%)
Gainesville, Florida[4]	0 (0.00%)	226 (100.00%)	55 (18.82%)	239 (81.18%)
Summer				
Buffalo, New York[5]	90 (35.40%)	164 (64.60%)	143 (47.53%)	158 (52.47%)
New York city, New York[6]	146 (9.64%)	1,366 (90.36%)	184 (9.98%)	1,660 (90.02%)
Charlotte, North Carolina[7]	16 (6.70%)	227 (93.30%)	52 (16.13%)	270 (83.87%)
Bridgeport, Connecticut[8]	142 (100.00%)	0 (0.00%)	82 (47.92%)	90 (52.08%)
Hartford, Connecticut[9]	119 (100.00%)	0 (0.00%)	128 (90.85%)	13 (9.15%)
Fall				
Buffalo, New York[10]	90 (37.84%)	148 (62.16%)	143(50.81%)	138 (49.19%)
Albany, New York[11]	0 (0.00%)	115 (100.00%)	86(61.69%)	53 (38.31%)
New York city, New York[12]	823 (58.15%)	592 (41.85%)	549(31.82%)	1,176 (68.18%)
Charlotte, North Carolina[13]	0 (0.00%)	227 (100.00%)	104(34.49%)	197 (65.51%)

[1] Charlotte-Asheville-Hickory, NC1
[2] Charleston-Myrtle Beach, SC3
[3] Augusta-Savannah, GA2
[4] Gainesville-Jacksonville-Ocala-Pensacola-Tallahassee, FL3
[5] Buffalo-Rochester-Syracuse-Utica,NY1
[6] NYC, NY3
[7] Charlotte-Asheville-Hickory, NC1
[8] Bridgeport-NewHaven, CT1
[9] Hartford-Norwich, CT2
[10] Buffalo-Rochester-Syracuse-Utica, NY1
[11] Albany-Poughkeepsie, NY2
[12] NYC, NY3
[13] Charlotte-Asheville-Hickory, NC1

Charleston, South Carolina[14]	0 (0.00%)	78 (100.00%)	56(50.77%)	54 (49.23%)
Durham, North Carolina [15]	242 (91.39%)	23 (8.61%)	137(39.29%)	212 (60.71%)
Gainesville, Florida[16]	0 (0.00%)	209 (100.00%)	28(10.17%)	245 (89.83%)
Winter				
Augusta, Georgia[17]	0 (0.00%)	74 (100.00%)	55 (57.65%)	41 (42.35%)
Deltona, Florida[18]	0 (0.00%)	598 (100.00%)	792 (78.55%)	216 (21.45%)

Source: Authors' calculations based on the optimization models.

[14] Charleston-Myrtle Beach, SC3
[15] Durham-Winston-Greensboro-Raleigh-Fayetteville, NC2
[16] Gainesville-Jacksonville-Ocala-Pensacola-Tallahassee, FL3
[17] Augusta-Savannah, GA2
[18] Deltona-Orlando-Palm Bay-Port Saint Lucie-Pompano Beach, FL2

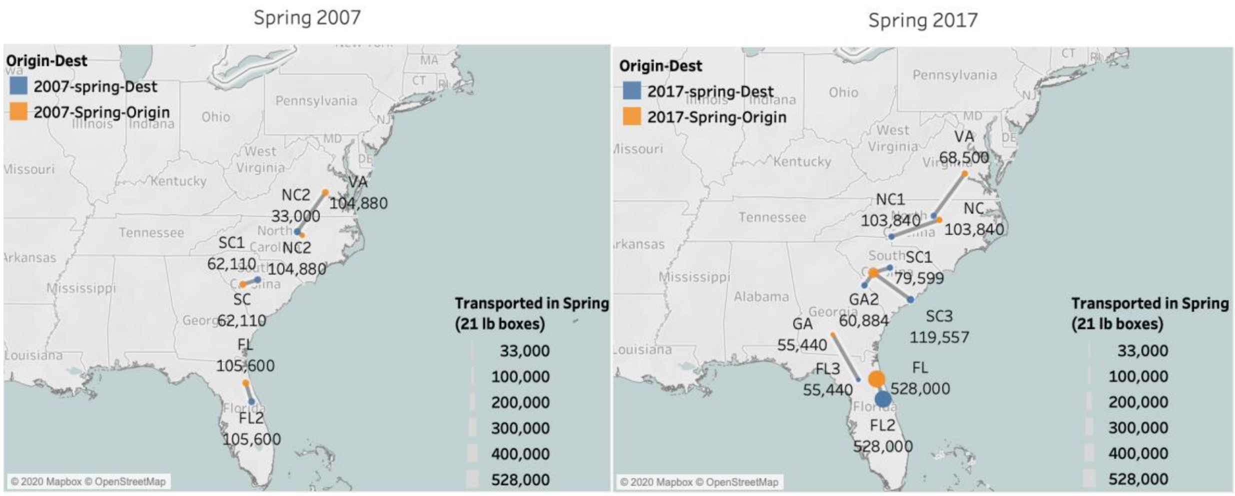

Fig. 1. U.S. eastern broccoli supply chain flows in spring 2007 and 2017. *source*: Generated from optimization models.

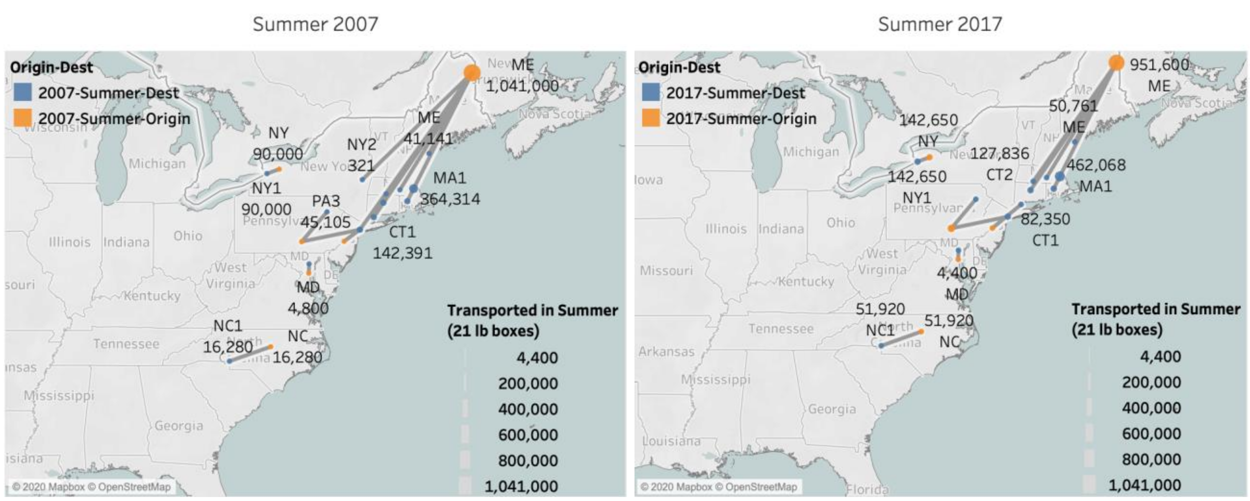

Fig. 2. U.S. eastern broccoli supply chain flows in summer 2007 and 2017. *source*: Generated from optimization models.

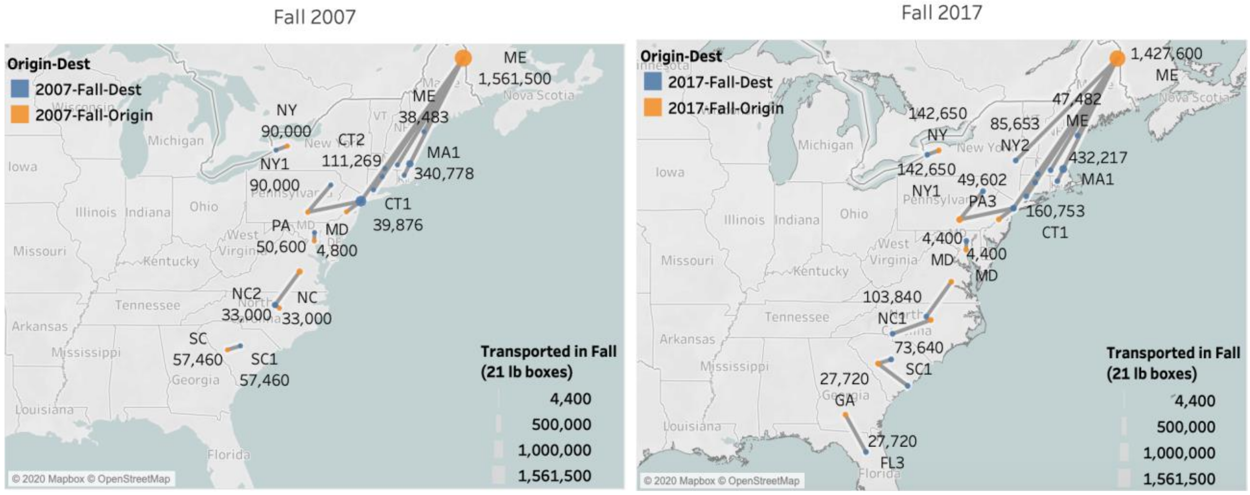

Fig. 3. U.S. eastern broccoli supply chain flows in fall 2007 and 2017. *source*: Generated from optimization models.

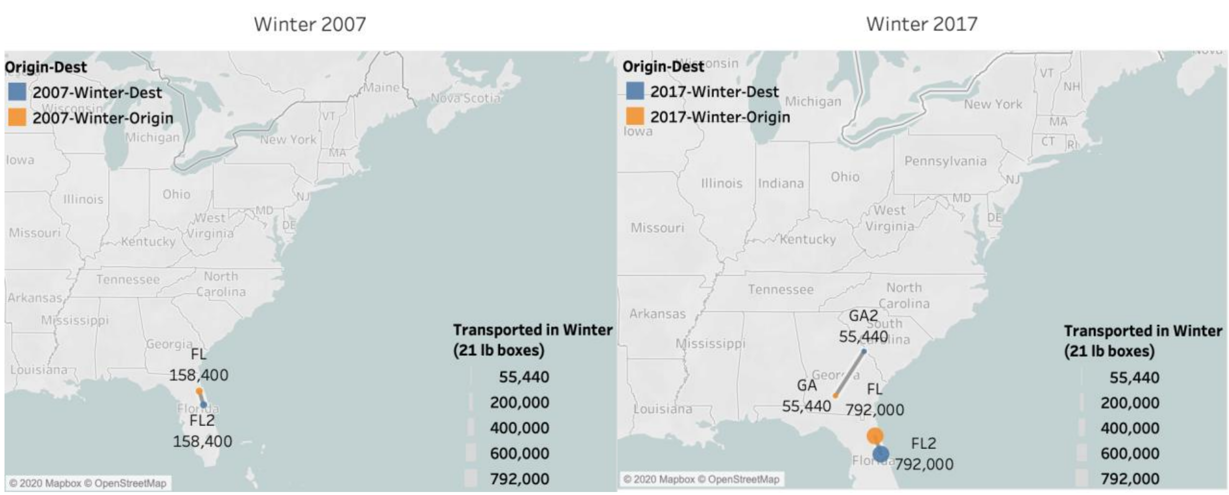

Fig. 4. U.S. eastern broccoli supply chain flows in winter 2007 and 2017. *source*: Generated from optimization models.

Table 6

Changes on weighted average source distance (WASD) travelled from different supply systems in U.S. eastern market in 2007 and 2017.

	2007	2017	Change	% Change
WASD (miles)				
WASD of all national sourced broccoli (*NWASD*)				
Spring	2,520	2,559	39	1.56%
Summer	2,342	2,403	61	2.61%
Fall	1,806	2,141	335	18.56%
Winter	2,345	2,602	257	10.95%
Annual	2,262	2,432	171	7.54%
WASD of eastern sourced broccoli (*EWASD*)				
Spring	111	130	20	18.01%
Summer	383	287	-96	-25.11%
Fall	408	324	-84	-20.59%
Winter	158	160	2	1.16%
Annual	365	255	-110	-30.07%
WASD of mainstream sourced broccoli (*MWASD*)				
Spring	2,625	2,845	220	8.39%
Summer	2,726	2,798	73	2.67%
Fall	2,373	2,780	407	17.16%
Winter	2,391	2,834	444	18.55%
Annual	2,533	2,817	284	11.21%

Source: Authors’ calculations based on the optimization models.