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Localization effects for a fresh vegetable product supply chain: Broccoli in the eastern United States

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ABSTRACT

What are the costs of increased food system localization in the case of a fresh vegetable product? When production is reallocated across space and seasons, how do supply chain costs and consumer prices change? In this article, we use a production and transportation model to answer these questions, along with illustrative simulation results from increased production of fresh broccoli in the eastern United States. Contrary to previous findings in other industries, we find that localization through reallocation of production may take place at no cost to the consumer, even at a small decrease in price. Localization may also reduce total broccoli supply chain costs and food miles.

Introduction

An alternative food supply system is a priority shared among some consumers, producers and governments. Consumers are increasingly aware of the social and environmental impacts of food systems (e.g. Weatherell et al., 2003; Brown et al., 2009). Growers and retailers constantly innovate to reduce costs while responding to consumer demand for alternative ways to produce and distribute food such as regional and local food systems (e.g. Gilg and Battershill, 1998; Broderick et al., 2011) and to the resulting shifts in public policy (e.g. USDA, 2013 and Kneafsey et al., 2013). Many of these goals may be achieved by diversifying where food is produced. However, the food system localization resulting from production reallocation across space and seasons may have unintended consequences such as increasing supply chain costs and prices paid by consumers. Localization can also alter the supply chain structure, chiefly product flows, in spatially and seasonally unexpected ways. Examination of supply-chain localization impacts requires models and methods that address the spatial and seasonal components of the supply chain, particularly in the case of fresh fruits and vegetables. Efforts to increase production in new areas need to be informed by analyses of the optimal locations of increased production and the effects of localization on production and transportation costs, consumer prices, and product flows.

Such localization effects vary among food commodities. In this paper, we develop an optimization model that depicts the production and transportation of a perishable product, fresh broccoli. We calibrate the model using both primary and secondary data for the United States (U.S.). The model can be solved for the locations and seasons that increase eastern broccoli production while minimizing total costs of production and transportation. We simulate and analyze scenarios of optimal broccoli acreage expansion in the eastern U.S. We measure the resulting changes in system-wide costs by supply segment and season; changes in product marginal costs; increases in the share of eastern-produced broccoli in eastern markets; and decreases in the weighted average source distance (WASD) travelled by the product from farm to demand location (food miles).

The U.S. fresh vegetable sector is an excellent setting for examining the economic and environmental impacts of increased localization of food supply chains. Many vegetables are disproportionally produced in California largely because of its favorable climatic zones and soil (Duxbury and Welch, 1999). This supply concentration is, however, highly dependent on subsidized and limited irrigation water supplies (Peters et al., 2002). Increasing competition for declining water resources between urban and agricultural needs, combined with increasing truck rates,[1] will reinforce the advantages of spatially diversifying vegetable production.

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[1] Real truck rates have increased by 39% between 2003 and 2011 (Prater et al., 2014).

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Broccoli is an interesting case study for examination of the economic consequences of increased localization in fresh vegetable supply chains. Lessons learned from studying broccoli might be generalizable to other fresh crops in the U.S. that share the following characteristics: (1) they are consumed nationally but mostly produced in the western U.S; (2) reallocating some of their production to other regions is possible if new varieties are developed; (3). unless produced in greenhouses, expanding their production in the eastern U.S. would be limited to the summer-fall season. Examples of such crops include carrots, celery, chicory, endive, grapes, strawberries, and lettuce.

Although few locales in the U.S. can supply horticultural commodities year-round as California does, the development of new broccoli varieties adapted to the agroecological conditions of the eastern U.S. is an opportunity for spatial diversification in the national horticultural supply chain. Such diversification might reduce water and energy needs while keeping the industry competitive. Broccoli is a high-volume commodity, with U.S. consumption at about 2 billion pounds per year (USDA, 2010). Warm summer nights make it impossible to produce high quality broccoli in most parts of the eastern U.S. Maine, which enjoys cool summer nights, already produces broccoli for eastern markets in the summer-fall season. Currently, a consortium of public and private institutions is developing new broccoli varieties adaptable to the eastern U.S. in order to satisfy: consumer demand for sustainable, locally-grown, healthy food; grower demand for high-value specialty crop varieties; retailer demand for lower transportation costs, and public sector pressure for reduced carbon emissions and a more reliable food system.[2] This project offers the opportunity to examine the economic impacts of increased localization in a horticultural supply chain. Policy makers supporting local and regional food systems (e.g. USDA, 2013 and Kneafsey et al., 2013) want to identify optimal location-seasons for acreage increases and evidence on localization impacts on costs and prices. Producers and packer–shippers might be interested in anticipating the magnitude, location and seasonality of expected product flows in the wake of acreage expansion in the eastern U.S. Finally, consumers need information on whether localization might increase marginal costs and consumer prices.

Literature review

The U.S. supply of fruits and vegetables may be increasingly vulnerable because much of the nation's horticultural supply is concentrated in water-scarce, drought-prone California (Duxbury and Welch, 1999). Climate changes are likely to further reduce the availability of irrigation water in California (Weare, 2009). Recent droughts in California have caused groundwater depletion to become unsustainable at current recharge rates (Scanlon et al., 2012).

One strategy to reduce supply vulnerability consists of relocating some production to areas with higher rainfall and fewer droughts. However, spatial diversification of supply in the U.S. can be a challenge because most horticultural crops are harvested from hybrid cultivars specifically developed for California production environments (Björkman, 2010). Broccoli, one of the top dollar vegetables produced domestically with a farm-gate value of $800 million (USDA, 2010) is no exception. Although some new broccoli cultivars have been tested in the eastern U.S., adaptation to eastern production conditions has not been an objective of U.S. breeding programs until recent years (Björkman, 2010).

Aside from the obvious challenge that broccoli cannot grow during winter months in much of the eastern U.S., relatively warm summer evenings can reduce its marketable yield. In response, the U.S. Vegetable Laboratory and Cornell University are breeding broccoli cultivars adapted to summer conditions of the eastern U.S. (Farnham and Bjorkman, 2011). One project currently aims at developing new varieties tailored to year-round eastern production from northern Florida to Maine. Although current U.S. production is largely centered in California, eastern production in Maine is well established, and there is increased interest in growing broccoli in other eastern states.

While new broccoli cultivars are developed, regional testing takes place, and hybrid seed production starts, effects of a regional production increase on the supply chain need to be better understood. The recent literature on food system localization focuses mostly on understanding consumer demand (Onozaka et al., 2010; Sirieix et al., 2008; Toler et al., 2009) and willingness to pay for locally-grown food (Conner et al., 2009; Khan and Prior, 2010; Toler et al., 2009). Another stream of the literature, however, deals with supply chains and the response to food system localization and the economic and environmental consequences that follow. The most common concept or metric used to quantify food system localization is the one of food miles; it represents the distance traveled from field to consumer (Coley et al., 2009; Hein et al., 2006). Using this measure, three Iowa case studies showed that food produced within local or regional food systems travels fewer miles than the food produced within a conventional system (Pirog and Benjamin, 2005). Localization effects can, however, sometimes go in the other direction. King et al. (2010) show that, for some food products, fuel use per unit of food product can be higher in local supply chains compared to mainstream supermarket supply chains which often enjoy higher efficiencies in transportation, storage, and distribution. Few studies provide more comprehensive estimates of the changes in supply chain costs due to localization. In the foodservice sector, Hardesty (2008) shows that transaction costs in localized supply chains are larger than in mainstream chains. Studying U.S. dairy supply chain segments beyond the farm gate for multiple products, Nicholson et al. (2011) found that, while localization cost impacts can be modest, they can impose relatively large cost re-allocations across supply chain segments, regions and products.

Methods

In this paper, we develop a mathematical programming, production–transportation model to identify the current optimal supply chain structure for fresh broccoli in the U.S. We then simulate increased localization by optimally expanding eastern production and analyzing the resulting seasonally- and spatially-disaggregated changes in the supply chain.

Production–transportation problems consist of deriving the production and transport patterns that minimize total production and transportation costs. Production needs to meet consumer demand, constrained by production capacity. In this study, we seasonally and spatially disaggregate the economic model. The model specifies seasonal supply and demand, regional production costs, and seasonal transportation costs. Given these inputs, the model solves for the production quantities and product flows that minimize the total cost of producing and shipping broccoli in each season. The model solution also provides, for each season, the resulting shadow prices for land at each supply location and the marginal costs of broccoli at the demand locations. We analyze the impact of a short-run eastern U.S. broccoli acreage expansion on production and transportation costs, the spatial–seasonal reorganization associated with optimal production and flows, and the reduction in weighted average distance travelled by the product.

We choose a supply chain approach because it allows us to analyze comparative advantages in both the production (yield,

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[2] For more details on the eastern broccoli project: http://www.hort.cornell.edu/bjorkman/lab/broccoli/easternindustrymain.php.

Table 1
Estimated U.S. broccoli acreage (2010), number of farms (2007), and yield.

	Broccoli acreage[a]				Number of farms[b]	Yield[c] (21lb boxes/acre)
	Spring	Summer	Fall	Winter		
Florida	504	0	0	756	52	440
Georgia	300	0	150	300	29	440
Maine	0	3300	2200	0	71	500
Maryland	0	145	145	0	40	400
New Jersey	0	69	69	0	74	450
New York	0	400	400	0	270	450
North Carolina	320	160	320	0	138	440
Coastal	200	100	200	0	86	440
Mountains	120	60	120	0	52	440
Pennsylvania	0	100	100	0	218	550
South Carolina	600	0	300	0	23	440
Central	500	0	250	0	19	440
Coastal	100	0	50	0	4	440
Virginia	367	0	735	0	75	570
Northern	325	0	650	0	66	570
Southwest	42	0	85	0	9	570
Total eastern U.S.	2091	4174	4419	1056	990	n/a
Arizona	5000	0	5000	15,000	44	600
California	32,650	32,650	32,650	32,650	416	800
Total western U.S.	37, 650	32,650	37,650	47,650	460	n/a
Total U.S.	39,741	36,824	42,069	48,706	1450	n/a
Eastern share (%)	5	11	11	2	68	n/a
Western share (%)	95	89	89	98	32	n/a

n/a: not applicable.
[a] Author's estimations from USDA-NASS Census of Agriculture (2007) and validation with Eastern broccoli project extension leaders; Atallah and Gómez (2013).
[b] USDA ERS (2011a) and validation with Eastern broccoli project extension leaders.
[c] Atallah and Gómez (2013) and crop budget references therein.

production cost, and seasonal land availability) and transportation (distance to markets and seasonal transportation costs) segments that vary across and within regions; treating these segments separately might otherwise lead to sub-optimality and misleading conclusions (Jolayemi and Olorunniwo, 2004). We disaggregate the analysis by season because of the seasonal and perishable nature of broccoli.

Broccoli supply, demand, and transportation data

The supply, demand, and transportation data include seasonal acreage available for fresh broccoli production, yields, and production costs at each supply location; seasonal volumes demanded and seasonal transportation costs; and distances between supply and demand locations.

Supply locations include 13 fresh-broccoli-producing 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 17 broccoli supply regions. The fresh-broccoli-producing regions in the eastern U. S. are located in Maine, New York, New Jersey, Pennsylvania, Virginia, Maryland, North Carolina, South Carolina, Georgia, and Florida. State level production was disaggregated when data allows doing so. Accordingly, Virginia, North Carolina and South Carolina are split in two multi-county regions each. According to the Census of Agriculture (USDA ERS, 2011a), the total number of broccoli farms in the 13 eastern U.S. locations in this study amount to 990 (Table 1). They produce 2–5% of broccoli produced nationally in the winter–spring season and about 11% in the summer-fall season. In contrast, 460 farms in California and Arizona produce 95–98% and 89% of national broccoli in the winter–spring and summer-fall seasons, respectively.

We use regional broccoli acreage estimates (USDA ERS, 2011a) and complement them with estimates from agricultural extension personnel in the respective regions (Jeanine Davis, Wythe Morris, Monica Ozores-Hampton, and J. Powell Smith, personal communication, 2012). We employ production cost estimates and yields available from existing regional broccoli crop budgets (see state-by-state references in Atallah and Gómez, 2013). When data were not available, we visited growers and packer/shippers to assemble necessary data (Atallah and Gómez, 2013). Table 1 shows estimated U.S. broccoli production in each region and season.

The model has 78 demand locations. We use the large metropolitan statistical areas (US Census, 2010), or MSAs, to define 42 demand locations in the eastern U.S.[3] In order to minimize the total number of demand locations in the model, we define one demand node per state for the four eastern states with less than two million people (Delaware, New Hampshire, Rhode Island and Vermont). We do the same for all the 32 non-eastern states and locate the nodes at the state centers of population (US Census, 2010). In the model, we consider fresh broccoli shipped by truck, which constitutes more than 93% of total fresh broccoli shipped in the U.S. (USDA ERS, 2011a).

Our consumption calculations use USDA's per capita domestic disappearance estimates (USDA ERS, 2011a).[4] Consumption is allocated to the MSAs and the state geographic centers based on population levels (US Census, 2010).[5] We use the seasonality in the U.S. fresh-market broccoli total monthly shipments for 2010 as a proxy for seasonal differences in domestic consumption (Table 2, based on USDA ERS, 2011a). Supply and demand quantities are measured in 21-lb broccoli boxes.

We use the shortest routes to compute the shipment distances between production locations and MSAs.[6] For the distance between production locations and demand locations defined at the state level,

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[3] We merge certain MSAs into single demand nodes (see Appendix for a full list).

[4] USDA's per capita domestic disappearance is computed as follows: U.S. export and shrinkage volumes are subtracted from U.S. import and domestic production volumes to estimate net domestic use. The latter is divided by the estimate of the U.S. population to obtain the per capita domestic disappearance (USDA ERS, 2012).

[5] We add non-metropolitan demand in each state to that state's metropolitan statistical areas in a way that is proportional to their populations.

[6] We compute the distance from a production location to a demand location representing two MSAs or more as the average of the distances from that production location to each of the MSAs.

Table 2
Seasonality of 2010 fresh broccoli shipment (domestic and imports), as a proxy of demand seasonality. *Source:* USDA ERS (2011a).

Season	Share (%)
Spring	27
Summer	21
Fall	23
Winter	29
Total	100

we use the U.S. state spatial distance matrix in Yu (2007). We use USDA's quarterly agricultural refrigerated truck rates (USDA, 2010) to compute shipment costs.

Model formulation

The model is formulated as an integrated production–transportation planning problem as follows (Eqs. (1)–(4)):

$$\text{Minimize}\sum_i^I\sum_k^K prod\_cost_i * Prod_{i,k} + \sum_i^I\sum_j^J\sum_k^K tr\_cost_{i,j,k} * miles_{i,j} * Trans_{i,j,k} \quad (1)$$

Subject to:

$$\sum_j^J Trans_{i,j,k} \le Prod_{i,k} \quad (2)$$

$$\frac{Prod_{i,k}}{yield_i} \le land_{i,k} \quad (3)$$

$$\sum_i^I Trans_{i,j,k} \ge demand_{j,k} \quad (4)$$

The problem is to find the production levels, $Prod_{i,k}$ (in boxes), at origin i and season k, and the seasonal product flow, $Trans_{i,j,k}$ (in boxes) from origin i to destination j in season k, that minimize overall supply chain costs (Eq. (1)). *ORIG*, *DES*, and *SEAS* are the sets of origins, destinations, and seasons, respectively. The first term of Eq. (1) specifies total production costs where $prod\_cost_i$ is origin i's average total production cost ($/box). The second term specifies total transportation costs where $tr\_cost_{i,j,k}$ is the unit transportation cost ($/mile/box) from origin i to destination j in season k and $miles_{i,j}$ is the distance between origin i and destination j (miles).

Seasonal supply constraints (Eq. (2)) ensure that the number of broccoli boxes shipped from each origin does not exceed the production level at that origin, in each season. The term $yield_i$ (in boxes/acre) is origin i's fresh broccoli yield, and Eq. (3) imposes constraints on the acreage available for broccoli production ($land_{i,k}$) at each location i, in each season k. Finally, seasonal demand constraints (Eq. (4)) ensure that product demand $demand_{j,k}$ is met at each location i, in each season k.

Optimal eastern acreage expansion scenarios

The baseline model solves for the optimal locations and seasons of an eastern broccoli acreage increase. It does so by computing the shadow prices on land in all locations and seasons. These shadow prices can be interpreted as the decrease in the total production and transportation costs associated with a one-acre increase in available land in each location and season. We use these shadow prices on land and the ranges over which they hold to guide recursive estimates of optimal acreage increases. That is, we increase land allocated to broccoli production in the supply location-season combination with the largest shadow price until the shadow price for that particular supply location-season changes. Then, we resolve the optimization model with the new added land to broccoli production. Subsequently, we use the new shadow prices to identify the next supply location-season combination with the largest shadow price for land, and increase the acreage allocated to broccoli production, and so forth. We follow this procedure until total eastern broccoli acreage has increased by 100%.

This method is conceptually sound but does not account for the opportunity cost of shifting land out of other crops and into broccoli in the eastern U.S. We argue in the 'Results' section that failure to consider this opportunity cost is not problematic because the simulated broccoli acreage increase is a small proportion of total acreage of fresh vegetable crops in the respective eastern states. We summarize the analysis by reporting the impact of eastern acreage expansion on the system's production and transportation costs and consumer prices, the spatial–seasonal reorganization of optimal production and flows, and the average distance travelled by the produce.

For the latter measure, we use the weighted average source distance, or WASD, a measure commonly used in food system studies (Berruto and Busato, 2009) to calculate a single distance figure that combines information on the distances from producers to consumers and the amount of product transported (Carlsson-Kanyama, 1996). Specifically:

$$\text{WASD} = \frac{\sum_i^{ORIG}\sum_j^{DEST}\sum_k^{SEAS} miles_{i,j} * Trans_{i,j,k}}{\sum_i^{ORIG}\sum_j^{DEST}\sum_k^{SEAS} Trans_{i,j,k}} \quad (5)$$

We also measure how the eastern broccoli share in eastern markets changes under the acreage increase scenarios such that:

$$Eshare = \frac{\sum_e^{EORIG}\sum_f^{EDEST}\sum_k^{SEAS} Trans_{e,f,k}}{\sum_i^{ORIG}\sum_f^{EDEST}\sum_k^{SEAS} Trans_{i,f,k}} \quad (6)$$

Eshare is the share of broccoli sold in eastern markets that is produced in eastern U.S. states, where *EORIG*, and *EDEST* are the sets of origins and destinations in the eastern U.S., respectively. In other words, it is the share of 'regionally produced' broccoli in the eastern U.S.

Results

The baseline model simulations under current broccoli production and distribution patterns indicate that supply chain costs for 2010 amounted to $1.22 billion (Table 3), 82% of which are production costs. Production and transportation costs are highest in winter and spring and lowest in summer and fall. The baseline average distance traveled by the product is approximately 308 miles higher in the winter–spring season, compared to the fall-summer seasons (the difference between the baseline winter-and-spring WASD and the summer-and-fall WASD). As expected, more eastbound long-distance shipping takes place when the share of eastern broccoli in eastern markets is lowest. This share is 6–9% in winter and spring (Table 3). In fall and summer, however, this share is of the order of 30–33% (Table 3) due to availability of Maine's broccoli supply in these seasons (Table 1). The effect of more long-distance shipments in winter and spring offsets the effect of lower trucking rates in these seasons and causes total transportation costs to be higher than in summer and fall.

Optimal eastern broccoli acreage increase

We simulate incremental optimal regional acreage increases up to a total increase of 100%. Optimality here refers to the

Table 3
Localization effects on costs, distance traveled and share of eastern broccoli in eastern markets.

	2010	Eastern broccoli acreage increase scenarios								
	Baseline	15% Increase[a]			30% Increase			100% Increase		
	Value	Value	Change[b]	% Change[b]	Value	Change	% Change	Value	Change	% Change
Costs ($ million/year)										
Total costs	1220	1216	−4	0	1213	−7	−1	1197	−23	−2
Spring	330	330	0	0	330	0	0	323	−6	−2
Summer	267	263	−4	−1	262	−5	−2	259	−8	−3
Fall	283	283	0	0	281	−2	−1	274	−9	−3
Winter	341	341	0	0	341	0	0	341	0	0
Production costs	1005	1007	2	0	1008	2	0	1011	7	1
Spring	268	268	0	0	268	0	0	269	1	0
Summer	216	217	2	1	218	2	1	219	4	2
Fall	236	236	0	0	236	0	0	238	2	1
Winter	285	285	0	0	285	0	0	285	0	0
Transportation costs	215	210	−5	−2	205	−10	−5	186	−30	−14
Spring	61	61	0	0	61	0	0	54	−7	−11
Summer	51	46	−5	−10	44	−8	−15	40	−12	−23
Fall	47	47	0	0	45	−2	−4	36	−11	−23
Winter	56	56	0	0	56	0	0	56	0	0
WASD (miles)	1387	1357	−30	−2	1331	−55	−4	1210	−177	−13
Eastern share (%)	18	21	3	n/a	24	6	n/a	37	18	n/a
Spring	9	9	0	n/a	9	0	n/a	28	19	n/a
Summer	33	47	14	n/a	53	20	n/a	63	29	n/a
Fall	30	30	0	n/a	36	6	n/a	61	31	n/a
Winter	6	6	0	n/a	6	0	n/a	6	0	n/a

n/a: not applicable.

[a] Increases of 15%, 30%, and 100% in eastern broccoli acreage would translate into a reallocation of 0.2% (1733 acres), 0.4% (3523 acres), and 1.3% (11,752acres) of total eastern fresh vegetable acreage to broccoli, respectively.

[b] Changes and percentage changes under each acreage increase scenario are computed with respect to the 2010 baseline acreage.

allocation of new acreage according to the shadow prices on land in each location and each season, obtained from the optimal solution to the cost minimization problem (Section 'Optimal eastern acreage expansion scenarios'). We report the production locations and seasons affected by optimal acreage increases under scenarios of 15%, 30%, and 100% total eastern acreage increases in Table 4. The 15% acreage increase level is an interesting scenario to examine because, below this level, optimal acreage increase takes place only during the summer months in Mid-Atlantic production locations. At the 30% acreage increase level, by contrast, more than one region and more than one season are affected by optimal acreage increases: additional acreage is allocated to Mid-Atlantic production locations in summer and new acreage is allocated to Florida in fall. Finally, we do not simulate higher levels of acreage increase of more than 100% because, based on our discussions with the broccoli project extension leaders, eastern broccoli acreage increase beyond this would not be realistic for growers, particularly in the short run (Jeanine Davis, Wythe Morris, and J. Powell Smith, personal communication, 2012).

Table 4
Optimal broccoli acreage increase in production locations, by season.

	Optimal Broccoli Acreage Increase (acres)			Fraction of total vegetable acreage (%)[a]
	Spring	Summer	Fall[b]	
15% Acreage increase scenario				
Florida[b]	0	0	0	0
New Jersey	0	48	0	0
Pennsylvania	0	1684	0	3
Virginia	0	0	0	0
Total	0	1733	0	2
30% Acreage increase scenario				
Florida	0	0	1012	0
New Jersey	0	48	0	0
Pennsylvania	0	2462	0	4
Virginia	0	0	0	0
Total	0	2511	1012	1
100% Acreage increase scenario				
Florida	2810	0	2857	2
New Jersey	0	397	0	1
Pennsylvania	0	3501	0	6
Virginia	307	0	1880	8
Total	3117	3899	4736	3

[a] Ratio of additional acreage in a state suggested by our model over total fresh vegetable acreage in that state reported in USDA ERS (2011b).

[b] We only report the seasons and locations that are affected by the optimal acreage increase up to 100%.

The results indicate how optimal allocation of additional acreage reflects the comparative advantage of each production location in reducing both production and transportation costs in each season. An optimal regional acreage increase of 15% would place new acreage in the Mid-Atlantic in summer (Pennsylvania and New Jersey, Table 4). Under the 30% acreage increase scenario, additional acreage is allocated to Pennsylvania in summer and to Florida in fall. Between the 30% and 100% acreage increase scenarios, acreage is added in Mid-Atlantic production locations (Pennsylvania, New Jersey) in summer and southeastern locations (Florida, Virginia) in spring and fall. It should be noted that optimal allocation in this model does not account for the opportunity cost of shifting land out of other crops and into broccoli in the affected states. One way to put this opportunity cost in perspective is to measure how the simulated acreage increases in each state compare to total acreages for fresh vegetable crops in the respective states. Small shares imply that growers can accommodate added broccoli acreage with limited adjustments in farming operations. As shown in Table 4, simulated broccoli acreage increases in Florida, New Jersey, and Virginia constitute less than 1% of the total fresh vegetable acreage in these states, under the 15% and the 30% eastern acreage increase simulations. Pennsylvania's new broccoli acreage makes up 3% and 4% of the total fresh vegetable acreage in that state for these two scenarios, respectively. Under a 100% eastern acreage increase scenario, simulated broccoli acreage increase in New Jersey, Florida, Pennsylvania, and Virginia constitute 1%, 2%, 6%, and 8% of the total fresh vegetable acreage in these states, respectively. These relatively small magnitudes suggest that failure to consider opportunity cost is not problematic, with the possible exception of Pennsylvania and Virginia in summer, under the 100% acreage increase scenario.

Localization effects on costs

The simulations indicate that a projected 30% eastern broccoli acreage increase reduces the annual supply chain costs by 1% (Table 3). The cost decrease is the result of changes in production and transportation costs. Production costs increase by less than 1%. This increase is due to the higher production costs in eastern U.S. locations compared to the western U.S. supply locations. However, production cost increases are offset by a 5% decrease in transportation costs. Transportation cost decreases are driven by WASD reductions of 55 miles/box or 4% below baseline. Localization effects under two additional acreage increase scenarios (15% and 100%) are also shown in Table 3, but we do not discuss them here because they are qualitatively similar to the effect of a 30% acreage increase.

Localization effects on consumer prices

After examining the potential effects of increased localization on broccoli marginal costs, our results indicate that higher prices paid by consumers are unlikely. In fact, increased localization is associated with a decrease in the marginal cost of broccoli in some eastern demand locations due to decreased transportation costs. Not surprisingly, the marginal cost of producing and shipping broccoli decreases in the seasons and regions where acreage expansion occurs: decreases are expected in northeastern MSAs in summer under the 15% acreage increase scenario. Under the 30% scenario, marginal costs decreases extend to the fall season in southeastern MSAs. Cost decreases at the margin are less than $0.15/box (0.9%) and less than $0.39/box (2.2%) for the 15% and 30% acreage increase scenarios, respectively. In contrast, under the 100% acreage increase scenario, decreases in the marginal costs of broccoli reach $0.80/box (5%) in summer, in northeastern MSAs. They are of the magnitude of $0.43–0.61/box (2.6–3.6%) in Florida MSAs. These small changes in the marginal cost of a broccoli box due to localization are consistent with the relatively small proportion of transportation costs in total costs shown in Table 1 (less than 20%).

Localization effects on distance travelled

Our model shows that, if eastern acreage increases were to occur in a cost-minimizing way, WASD decreases are nonlinear. That is, the marginal WASD decrease is not constant for each additional increase in acreage. For eastern acreage increases below 15%, the marginal rate of WASD decrease is highest (10%, Table 5) and only the summer season is affected (Fig. 1). For acreage increases between 15% and 90%, WASD decreases occur at much smaller rates (1–4%) and in three seasons (fall, spring, and summer, Table 5). At the 90% acreage increase level, WASD decreases again at a marginal rate of 10% during the fall season. Note that despite the different path of WASD decreases in fall and summer, both reach the same level of reduction (about 23%) at the 100% acreage increase scenario (Fig. 1). Finally, and not surprisingly, seasonality in WASD reduction follows the seasonality of acreage increases. Specifically, no WASD decrease occurs in winter, small decreases occur in spring, and the largest decreases occur in summer and fall.

Localization effects on product flows

Supply chain localization is associated with a spatial reorganization of broccoli flows within the eastern U.S. as well as nationally. To illustrate, Table 6 presents changes in summer flows from selected eastern and western production areas to northeastern demand locations under 15%, 30%, and 100% acreage increase scenarios. Under the 15% scenario, shipments from Pennsylvania and New Jersey to New York City replace all the summer shipments from California and Maryland. They also replace 6% (50,000 boxes, Table 6) of the shipments originating from Maine. In contrast, flow reorganization in Baltimore and Philadelphia are only interregional with shipments from California replaced with shipments from Maryland and Pennsylvania.

Further acreage increases in Pennsylvania in summer do not cause any further flow reorganizations in New York City or Philadelphia (30% acreage increase scenario, Tables 4 and 6). By contrast, the model reduces shipments from California to Baltimore further than it did under the 15% scenario and replaces them with shipments from Pennsylvania. Under the 100% acreage increase scenario, additional acreage in Pennsylvania and New Jersey in summer causes flows from these states to replace even more shipments from Maine than in the other acreage increase scenarios. It should be noted that, even with a 100% optimal acreage increase in the eastern U.S., only 18% of the baseline shipments from Maine to New York City are affected (165,000 boxes, Table 6). Baltimore substitutes all of its shipments from California with shipments from Pennsylvania while no further reorganization takes place in Philadelphia.

Table 5
Marginal rate of WASD decrease with acreage increase. *Source:* authors calculations based on the optimization model.

	Marginal WASD decrease			
Percentage acreage increase	Fall	Spring	Summer	Winter
15	0	0	−10	0
30	−4	0	−5	0
45	−4	−2	−2	0
60	−1	−3	−4	0
76	−3	−3	−1	0
90	−10	−1	0	0
100	−3	−3	−1	0

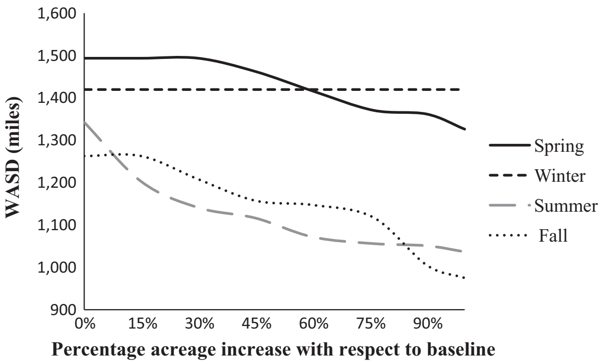

Fig. 1. Seasonal weighted average source distance (WASD) decrease with acreage increase.

Changes in broccoli flows in spring also cause reorganization at the interregional and intraregional levels. As a result of acreage increases in spring in Florida under the 100% scenario, the Cape Coral MSA in Florida substitutes all its shipments from Georgia with in-state shipments. In fact, under this scenario, shipments from Florida in spring replace all shipments from Mexico to the Augusta (Georgia) and Cape Coral (Florida) MSAs in that season (68,000 and 252,000 boxes, respectively, not shown in Table 6).

Discussion

These results provide new insights regarding localization of fresh vegetable crops and attendant effects on national system-wide costs, consumer prices, and supply chain food miles. First, our model suggests that increased localization does not necessarily lead to greater supply chain costs. In fact, we find that the 30% eastern acreage expansion scenario may increase eastern broccoli share in eastern markets (localization) by 6% without increasing supply chain costs or consumer prices. These results contrast with findings that localization of the dairy industry in the U.S. would generate higher total costs and large increases in consumer prices (Nicholson et al., 2011). This divergence in the findings underlines the ambiguity of localization effects and suggests the need for separate studies on the effects of localization for different types of food supply chains.

Second, the results illustrate how localization impacts can vary by supply chain segment. Given that eastern growers have higher broccoli production costs compared to California and Arizona (Atallah and Gómez, 2013) but are closer to more than one-third of the national demand, higher costs in the production segment are paired with decreased transport costs. Consumers benefit from lower transport costs but eastern producers bear the burden of higher production costs. Consequently, although eastern broccoli acreage expansion can be welfare-improving from a supply chain perspective, it may not occur unless eastern vegetable producers find it profitable to give up their current vegetable production to adopt the new broccoli varieties. This will critically hinge upon crop yields of newly developed varieties. Preliminary results from recent eastern broccoli variety trials suggest that yields in eastern production locations might be higher than those used in this study (Farnham, M.W., personal communication). In that case, per box production costs in the eastern U.S. would be lower, thereby offsetting to a certain extent the increased production costs ensuing from localization. Consequently, total system cost reductions would be larger than the 1% magnitude reported in this article and consumer prices might decrease even further.

Localization results might also differ depending on how the eastern broccoli industry expands. Lower shipping costs under localization will depend on how the eastern broccoli industry organizes product aggregation and cooling. In particular, decreases in transport costs are contingent on whether these two operations will be characterized by diseconomies of size due to the spatial configuration of farms. Finally, it should be pointed out that if fuel

Table 6
Simulated change in broccoli flows (1000 boxes) from eastern and western production sites to northeastern demand locations after 15%, 30% and 100% increase in eastern acreage, *summer* season.

	Demand locations		
Supply locations	New York City, New York[a]	Baltimore, Maryland[b]	Philadelphia, Pennsylvania[c]
15% Acreage increase scenario			
Maine	−50[d]	0	0
Maryland	−58	58	0
New Jersey	22	0	0
Pennsylvania	199	0	517
South Carolina, central	0	0	0
Virginia, northern	0	0	0
California	−113	−58	−517
30% Acreage increase scenario			
Maine	−50	0	0
Maryland	−58	58	0
New Jersey	22	0	0
Pennsylvania	199	119	517
South Carolina, central	0	0	0
Virginia, northern	0	0	0
California	−113	−177	−517
100% Acreage increase scenario			
Maine	−165	0	0
Maryland	−58	0	0
New Jersey	60	0	0
Pennsylvania	330	177	517
South Carolina, central	0	0	0
Virginia, northern	0	0	0
California	−113	−177	−517

[a] New York–Northern New Jersey–Long Island Metropolitan Statistical Area (MSA).
[b] Baltimore–Washington D.C.–Hagerstown MSA.
[c] Allentown–Harrisburg–Lancaster–Philadelphia–Reading–York MSA.
[d] Negative values indicate a decrease in flows from a production site to a demand location.

costs increase, the decrease in total supply chain costs due to localization would be greater, especially in the summer and fall seasons when trucking rates are highest. Fuel prices affect production costs too but to a far lesser extent compared to transportation costs (not shown in Table 3).

Third, our results indicate the location and season for an eastern broccoli acreage that would minimize the costs of production and transportation. The procedure we use to determine the optimal magnitudes, location, and seasonality of acreage increase can be applied to other supply chain models for other crops and other locations. Both policy makers and the produce industry might see actionable content in these results. In light of the scarce evidence on vegetable crop production localization effects, this analysis shows that localization may occur without increases in system costs or consumer prices. In addition, this study demonstrates that, even under large acreage increase scenarios (i.e., 100% acreage increase scenario), product flows from mainstream western production locations and the established eastern broccoli industry are minimally affected, if at all. For instance, the decrease in flows from Maine to New York City under the 30% acreage increase scenario constitutes only 6% of summer production in Maine. Similarly, the seemingly large decreases in volumes of California broccoli flows constitute only 3% of total California flows under the 30% eastern acreage increase scenario.

Conclusions

This paper makes a contribution through its integrated analysis of food system localization from a supply chain perspective. We used a production–transportation, supply chain model of the U.S. broccoli industry to analyze the effects of eastern broccoli acreage expansion and increased localization on supply chain costs, consumer prices, and average distance traveled. The primary conclusion is that increased localization does not necessarily increase total supply chain costs or consumer prices. This conclusion, however, depends on the production and transportation costs in the region where localization is taking place, relative to those in alternative supply regions.

Localization effects are seasonal, particularly for fresh horticultural crops, and intimately related to the production seasonality in the area undergoing localization. That relationship is especially close for highly perishable products such as fresh broccoli. Increased localization changes product flow at both the interregional and intraregional levels. Major flow reorganizations occur in summer under the high increase scenario whereby eastern demand nodes substitute long-distance shipments with East-to-East shipments. We expect the main results to be generalizable to other fresh horticultural crops supply chains characterized by a predominant production in the Western U.S. and a seasonality of production in the areas under study. Therefore, policy makers and industry practitioners should consider localization impacts of horticultural supply chains by segment, season, and location in order to appreciate the different impacts within the region undergoing localization.

Our model has identified several questions that deserve further investigation. Due to diseconomies of size, the costs of product collection and cooling can be important and variable depending on the spatial configuration of farms. The production–transportation model can be expanded to solve for the cost-minimizing locations of intermediate cooling facilities in eastern production areas. Including cooling facilities might also increase eastern transportation costs if the lower transportation cost due to less long-distance shipping is offset by the cost of aggregating product from many small, spatially spread eastern producers.

Although we show that simulated broccoli acreage increases in this study are a small fraction of total fresh vegetable acreages, failure to account for the opportunity cost of broccoli acreage expansion is limiting. Future research can include in the model the crops that compete with broccoli for land in each eastern state. Finally, our model assumes cost-minimizing behavior in the supply chain. This assumption should be validated by testing for market integration, efficiency of interregional commodity arbitrage, and imperfect competition. In sum, these limitations highlight the need for adding intermediate cooling locations in the model, including other crops, and complementing the study with market structure analyses.

Appendix A: List of demand nodes in the optimization model

1 Alabama
2 Arizona
3 Arkansas
4 California
5 Colorado
6 Bridgeport–New Haven, Connecticut
7 Hartford–Norwich, Connecticut
8 Connecticut, residual demand
9 Delaware
10 Cape Coral–Lakeland–Naples–North Port–Tampa, Florida
11 Deltona–Orlando–Palm Bay–Port Saint Lucie–Miami, Florida
12 Gainesville–Jacksonville–Ocala–Pensacola–Tallahassee, Florida
13 Florida, residual demand
14 Atlanta–Chattanooga–Columbus, Georgia
15 Augusta–Savannah, Georgia
16 Georgia, residual demand
17 Idaho
18 Illinois
19 Indiana
20 Iowa
21 Kansas
22 Kentucky
23 Louisiana
24 Portland–South Portland–Biddeford, Maine
25 Maine, residual demand
26 Baltimore–Washington D.C.–Hagerstown, Maryland
27 Maryland, residual demand
28 Boston–Cambridge–Quincy, Massachusetts–New Hampshire
29 Springfield, Massachusetts
30 Worcester, Massachusetts
31 Massachusetts, residual demand
32 Michigan
33 Minnesota
34 Mississippi
35 Missouri
36 Montana
37 Nebraska
38 Nevada
39 New Hampshire
40 Atlantic City, New Jersey
41 Trenton, New Jersey
42 New Jersey, residual demand
43 New Mexico
44 Buffalo–Rochester–Syracuse–Utica, New York
45 Albany–Schenectady–Troy, New York

46 New York City–Northern New Jersey–Long Island, New York – New Jersey –Pennsylvania
47 Binghamton, New York
48 New York, residual demand
49 Charlotte–Asheville–Hickory, North Carolina
50 Durham–Winston–Greensboro–Raleigh–Fayetteville, North Carolina
51 Wilmington, North Carolina
52 North Carolina, residual demand
53 North Dakota
54 Ohio
55 Oklahoma
56 Oregon
57 Erie, Pennsylvania
58 Pittsburg–Youngstown, Pennsylvania
59 Scranton, Pennsylvania
60 Allentown–Harrisburg–Lancaster–Philadelphia–Reading–York, Pennsylvania
61 Pennsylvania, residual demand
62 Rhode Island
63 Columbia, South Carolina
64 Greenville–Spartanburg, South Carolina
65 Charleston–Myrtle Beach, South Carolina
66 South Carolina, residual demand
67 South Dakota
68 Tennessee
69 Texas
70 Utah
71 Vermont
72 Lynchburg–Roanoke, Virginia
73 Richmond–Virginia Beach, Virginia
74 Virginia, residual demand
75 Washington
76 West Virginia
77 Wisconsin
78 Wyoming

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