Assessing the Conservation Value of High Tunnel Production and its Contribution to the Local Food Movement in the U.S.

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ABSTRACT

There is growing demand for food grown and sold locally, but climate often limits supply. High tunnels can often overcome these limitations. In order to encourage local availability and production of specialty crops the Natural Resource Conservation Service (NRCS) has launched the Seasonal High Tunnel initiative. This cost-share program provides farmers with a high tunnel intended to encourage the availability of locally grown fresh produce. Using mixed-methods research this thesis examines the social, economic, and conservation impacts of the NRCS high tunnel program. We have run a county by county negative binomial regression of the NRCS high tunnel distribution biophysical, socio-demographic, and market driven factors. Additionally, 7 vegetable farms throughout Virginia were visited during the 2014 growing season to compare high tunnel and field grown cucumbers (*Cucumis sativus*) and tomatoes (*Solanum lycopersicum*). Additional detail about high tunnel production and food distribution was obtained with a survey of Virginia high tunnel growers. Survey respondents indicate that the majority of their high tunnel produce is sold within 100 miles of their farm. Regression results indicate that the NRCS high tunnel program is benefiting areas where the availability of local food is high, but may be neglecting areas with historically underserved communities. Our field results show that yield and the yield per pesticide application dividend were higher in high tunnel production of both cucumber and tomato. Therefore, we conclude that, high tunnels meet conservation goals different than the ones outlined by the NRCS. The NRCS high tunnel program is promoting the expansion of local food availability. However, work remains to clarify conservational benefits and to ensure that all communities have equal access to the fresh produce they provide.

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ATTRIBUTION

Megan E. O'Rourke, PHD, Sustainable Food Systems lab, Horticulture department at Virginia Tech, is currently a professor of Sustainable Food Systems at Virginia Tech. Dr. O'Rourke is co-author on Manuscript 1 and 2 and contributed to the statistical techniques and writing.

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INTRODUCTION

Background

In 2010 the U.S. Department of Agriculture (USDA) Natural Resource Conservation Resource Service (NRCS) began to subsidize the construction of high tunnels via the Environmental Quality Incentive Program (referred to throughout this document as the NRCS high tunnel program). The NRCS high tunnel program allows each farm to receive one high tunnel per farm bill cycle. Since its start in 2009 the NRCS high tunnel program has paid for 9,489 high tunnels (Foust-Meyer and O'Rourke, 2015). With increasing demand for local food[1] in the U.S. (Low, 2015) it is important to assess the distribution of the NRCS high tunnels to understand where the produce is likely to be sold, and to verify the impacts of high tunnel production on farm conservation. Understanding how high tunnel production influences food availability, distribution and conservation will allow for better decision making in food system planning and the future subsidization of high tunnels.

High tunnel design and use

Extending the growing season by protecting plants from cold temperatures can drastically increase crop productivity in early spring, late fall, and even into winter (Jett, 2013; Lamont, 2005; Merrigan, 2010). Additionally high tunnel production may lead to increased availability of locally available fresh produce. Covered by clear polyethylene plastic, high tunnels trap heat, extend the growing season, and shelter crops from extreme weather events. High tunnels differ from conventional greenhouses because they are passively heated and ventilated, and the crops are planted directly into the soil. Similar to greenhouses, high tunnels trap heat and provide a growing environment that is easier for growers to control based on plant needs and conditions.

Constructed from wooden or steel frames, high tunnels are relatively inexpensive to construct. Most high tunnels are about 2,000 square feet in size and have construction costs between $2 and $4 per square foot. They can be built in the traditional Quonset hut style or with a peaked roof known as the gothic style (Orzolek, 2013). Some are built on tracks or skis so they can be moved down a row to accommodate seasonal crop needs. Ventilation is provided passively by vents on the sides of the high tunnel which can be rolled up during hot days and closed during cold days to retain heat (Everhart, Hansen, Lewis, Naeve, and Taber, 2010).

There are many crops that can be grown in high tunnels. High value specialty fruits, vegetables or cut flowers are among the most popular (Orzolek, 2013). Choosing crops that are suited to intense heat is important for summer production. Cucumbers (*Cucumis*

[1] Local food as defined by the U.S. Congress in the 2008 Food, Conservation, and Energy Act is any regionally or locally agricultural product produced within less than 400 miles (644 km) from its origin, or within the State in which it is produced (Martinez, 2010).

sativus) and tomatoes (*Solanum lycopersicum*) are among the most popular summer grown high tunnel crops. Others include peppers (*Solanum annuum*), eggplant (*Solanum melongena*), basil (*Ocimum basilicum*), or ginger (*Zingiber officinale*) (Jett, n.d.). High tunnels can also be used for winter production of cooking or salad greens, lettuce (*Lactuca sativa*), radishes (*Raphanus sativus*), carrots (*Daucus carota*), or other cool season crops.

High tunnels give farmers the chance to increase farm income by intensively managing high-value crops. It has been estimated that a standard sized high tunnel's net income (roughly 2,000 square feet) may only be slightly less than 1 acre of field grown mixed vegetables. This is attributed to planting and harvesting two or three crops per year in high tunnels. Depending on the crop mix and length of harvest (as long as late December in Virginia) high tunnels can potentially net a farm $3,000 to $10,000 in a single growing season (Chase, 2012).

High tunnels represent a small proportion of U.S. fresh produce acreage, but the popularity of high tunnels is growing. In 2008, high tunnel acreage was between 4,666 and 5,027 acres (Carey, et al.) compared with 334 million acres of total fruit and vegetable crop production in the U.S. (ERS, 2007). The primary advantage of high tunnel production is the potential for profit (Chase, 2012). High tunnels increase net returns by increasing yields (Lamont, 2005) and providing the opportunity to obtain higher prices for off season produce. High tunnels also ensure higher profits by lengthening the growing season and allowing growers to provide produce over a longer and more consistent period of time (Jett, 2013). Known disadvantages of high tunnel production include increased fixed costs associated with construction, and increased labor demands (Jett, 2013). However it is possible for high tunnel growers to quickly overcome these barriers and provide returns on investment within the first few growing seasons (Chase, 2012).

Local food and high tunnels

High tunnel production may contribute to the availability of local food because of earlier crop production (7 to 21 days earlier than in the field), the ability to double or triple crop, and higher yields per unit areas (two to three times higher). High tunnel production may also spur additional conservation benefits such as more efficient use of pesticides and lower disease incidence (Lamont, 2005). Each of these has the potential to help increase the local availability of fresh produce.

The delicate nature of most high tunnel products limits their ability to be shipped (Orzolek, 2013), which suggests that they will remain in the local food-system and contribute to direct-to-consumer markets. However, many critics of the local food movement say that it is a luxury of the urban middle class (Patel, 2007). Recent analysis of agricultural statistics supports this presumption. Low and Vogel (2011) found that agricultural direct sales are highest in metropolitan areas, especially those on the West Coast and Northeastern United States (Figure 3) where incomes tend to be high. This leads to the possibility that the NRCS high tunnel program may be disproportionately benefiting high income urban consumers.

Many of the impacts of high tunnel production on the food system remain to be studied. Demand for local food in the U.S. is growing (Low, 2015) and local foods have been touted as a means to shortening supply chains, increasing food sovereignty, and increasing agricultural sustainability (Feenstra, 1997). Because of their season extension capabilities, high tunnels are one means to increasing local food production. By analyzing the distribution of high tunnels, we can begin to answer the following questions: Who benefits from high tunnels and where in the U.S. are the benefits most abundant? What is the influence of high tunnels on local food production and distribution? We also report direct feedback from high tunnel growers in Virginia concerning the distance their high tunnel produce is traveling, the types of markets that it is being sold in, and the demographic characteristics of the growers.

Conservation and the NRCS high tunnel program

The NRCS high tunnel program has been designed to meet several conservation goals. These goals include: improving plant quality, reducing pesticide use, and reducing energy use by providing consumers with a local source of fresh produce (USDA, 2012). The conservation and environmental benefits of local food are highly contested (Ackerman-Leist, 2013). However, high tunnel production may make it possible to reduce pesticide and energy use by providing consumers with a local source of fresh produce. By reducing pesticide use and increasing crop yield, high tunnels may provide a new and verifiable conservation benefit to local food production.

Through the lens of the NRCS high tunnel program, this thesis explores the influence of high tunnel production on the local food system and environmental conservation. The advertised benefits and goals of the NRCS high tunnel program may not be as simple as they seem. There are many reports of high tunnels increasing yields and fruit quality, and plant quality (Rogers and Wszelaki, 2012; Hood, Little, Coatney, & Morgan 2011; O'Connell, Rivard, Harlow, Peet, & Louws, 2012). High tunnels have also been shown to reduce some crop diseases. However, if the farmer does not manage the high tunnels properly, yields can become equal or fall lower than those in the field (Pullano, 2015).

An overhaul of the language used in the NRCS high tunnel program may be necessary to accurately describe the environmental dynamics of high tunnel production. However, scientific literature is lacking on the subject. This portion of the thesis examines if high tunnels reduce pesticide use, increase plant quality, or increase the amount of locally available fresh produce.

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MANUSCRIPT 1

High tunnels for local food systems: Subsidies, equity, and profitability

Abstract
High tunnels are expanding opportunities to increase local food production in the midst of a globalized food system. They can overcome biophysical growing constraints by buffering temperatures to extend the growing season and shelter crops from extreme weather events. In 2010, the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) began subsidizing the purchase of high tunnels. However, many questions remain about the factors influencing participation in the program and its impacts. Using mixed-methods research, this paper assesses the biophysical, market, and socio-demographic factors influencing NRCS high tunnel adoption in the U.S. and examines how food production in high tunnels affects farmers, consumers, and the local food movement. Results show that the number of NRCS high tunnels per county increased in relation to a mixture of biophysical (high latitude, proximity to the coast, small average farm size, and high percent of farmland in vegetable production), market (high direct-to-consumer sales, good access to grocery stores, and high median household income), and

socio-demographic (high percentage of nonwhite population, metropolitan counties with more than 250,000 people, and adjacent urban counties with fewer than 20,000 people) factors. According to our survey of Virginia high tunnel growers, high tunnel produce is largely sold locally (within 50 miles or 80 km of production) and marketed direct-to-consumers in Virginia. Many growers in Virginia who would not have purchased a high tunnel without NRCS support plan to purchase additional high tunnels in the future even without a subsidy. High tunnels are an emerging part of the U.S. local food movement, but work remains to ensure that their benefits reach all sectors of U.S. society.

Introduction

Food insecurity[2] is on the rise globally (Khoury, Bjorkman, Dempewolf, Ramirez-Villegas, Guarino, Jarvis, Rieseberg, & Struik, 2014). Many attribute this to volatility in global markets and food supply (Food and Agriculture Organization [FAO], 2008). Other criticisms of the globalized food system include increasingly homogeneous production and consumption patterns (Khoury et al., 2014; O'Hara & Stagl, 2001), and negative impacts on personal health and quality of life (Kennedy, Nantel, & Shetty, 2004). In the search for solutions, increasing local food[3] production has been offered as one option to boost food security and combat the ill effects of globalization (Porter, Dyball, Dumaresq, Deutsch, & Matsuda, 2014).

In the United States, local food production and consumption is on the rise. From 1992 to 2007, direct-to-consumer sales grew from US$404 million to US$1.2 billion, growing twice as fast as total agricultural sales in the U.S. (Tropp, 2010). Local food's market share has since expanded to US$6.1 billion in 2012, which is approximately 1.5% of total U.S. farm sales (Low et al., 2015). The amount of food that can be grown, marketed directly to consumers, and consumed locally is often limited by market capacity and biophysical growing constraints (Martinez et al., 2010; Timmons, Wang, & Lass, 2008). High tunnels are emerging as a technology that can increase local food production by protecting crops from cold temperatures and extreme weather events (Hood, Little, Coatney, & Morgan 2011; O'Connell, Rivard, Harlow, Peet, & Louws, 2012).

While there are a variety of high tunnel designs, most share several common attributes. They are covered by clear plastic, passively heated by solar energy, and built directly over the soil (Lamont, McGann, Orzolek, Mbugua, Dye, & Reese, 2002). One high tunnel typically covers an area of around 2,000 square feet (186 square meters) (University of Illinois Extension [UIE], 2014). The cost of construction is roughly US$2 per foot^2 (0.1 m^2) (Coolong, 2012), which is much less than constructing a conventional greenhouse (Hood et al., 2011; Ochterski, 2012). They are predominately used to produce high-value and specialty produce (Cheng & Uva, 2008; Winter, 2008). One standard high tunnel (30 x 70 ft. or 9 x 21 m) with 195 slicer tomato plants could net as

[2] "Food security exists when all people, at all times, have physical and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO, 2008).

[3] Local food as defined by the U.S. Congress in the 2008 Food, Conservation, and Energy Act is any regionally or locally agricultural product produced within less than 400 miles (644 km) from its origin, or within the State in which it is produced (Martinez, 2010).

much as US$5,200 in a single growing season (Chase, 2012). This equates to approximately US$100,000 per acre,[4] compared to netting US$20,000 per acre per year for high-value vegetables grown in the field (Chase, 2012).

The affordability of high tunnels and their potential to extend the growing season have made them profitable for a growing number of farmers (Carey, Jett, Lamont, Nennich, Orzolek, & Williams, 2009; National Center for Appropriate Technology, 2009). Survey data collected at three farmers markets in Michigan showed that customers were willing to pay premium prices for salad greens, spinach, and tomatoes late and early in the year (Conner, Montri, Montri, & Hamm, 2009). Forty-nine percent of the respondents indicated that they would pay up to US$3.00 extra per head of lettuce in the winter months (Conner et al., 2009). Additionally, growers report that high tunnels help them to retain their customer base because they have produce to sell more consistently throughout the year (Arnold & Arnold, 2003).

High Tunnels and the NRCS

To support the growing demand for local foods, the USDA instituted the "Know Your Farmer, Know Your Food" initiative to increase the connection between all levels of agricultural production and the consumer (USDA, 2013). In support of this initiative, the USDA tasked the Natural Resources Conservation Service (NRCS) with administering the Seasonal High Tunnel (SHT) initiative in 2009 (referred to throughout this paper as the NRCS high tunnel program), under the umbrella of the Environmental Quality Incentives Program (EQIP). In 2011, USDA then–deputy secretary Kathleen Merrigan made a statement attempting to directly link the NRCS high tunnel program with benefits to the local food system:

> By capturing solar energy, seasonal high tunnels create favorable conditions enabling farmers to grow vegetables, berries, and other specialty crops in climates and at times of the year in which it would not be possible otherwise. Farmers who sell their high tunnel produce locally benefit from the extra income and the community benefits from the availability of fresh, locally grown food. (Merrigan, 2010)

The NRCS also stated a goal of serving historically underserved groups of farmers, including beginning (those operating their current farm for less than two years) (USDA NASS, 2014), and non-white farmers (USDA NRCS, 2014).

Under the NRCS high tunnel program, individual farms have been eligible to receive up to US$4,116 toward the construction of a 2,178 square foot (202 m^2) or smaller high tunnel (USDA NRCS, n.d.). After four years of government support in the U.S., it is time to examine the factors driving NRCS high tunnel adoption and to explore their impacts. Specifically, this paper will address the following questions:

(1) Where have NRCS high tunnels been built?
(2) What influence do biophysical, market, and socio-demographic factors have

[4] 1 acre = 0.4 hectare

on NRCS high tunnel adoption and distribution?

(3) Are high tunnels helping farmers, consumers, and/or the local food movement?

Methods

To address our research questions, we employed mixed-methods research strategies. These included geographic information system (GIS) mapping and statistical analysis of the nationwide distribution by county of NRCS high tunnels in relation to county-level biophysical, market, and socio-demographic factors. We also surveyed a subsample of high tunnel growers in Virginia to better understand how some farmers use high tunnels, and whether they are satisfied with the NRCS high tunnel program.

GIS High Tunnel Mapping

High tunnels funded by the NRCS from January 2010 through December of 2013 were mapped to show their distribution throughout the U.S. Data about NRCS high tunnels were obtained through a Freedom of Information Act request. High tunnel population data were totaled and mapped using ArcMap 10.1. To estimate total growing space covered by NRCS high tunnels, each high tunnel was assumed to be 2,000 ft^2 (186 m^2) (UIE, 2014).

Regression Analysis

A generalized linear model was constructed to examine relationships between county-level biophysical, socio-demographic, and market variables and the total number of NRCS high tunnels adopted per county in the U.S. until December 2013. The analysis used a negative binomial regression (O’Hara & Pirog, 2013) to account for non-normal and overdispersed data. All statistical calculations were executed using R 3.0.2 (R Development Core Team, 2010).

The biophysical variables that were examined included latitude (U.S. Census Bureau, 2014), location outside the arid Midwest, average farm size (in acres) (USDA NASS, 2014), and vegetable production acreage (USDA NASS, 2014). Each was analyzed to describe a county’s location and agricultural growing conditions (Wielgolaski & Inouye, 2003). States considered as “arid Midwest” (Arizona, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, South Dakota, Texas, Utah, and Wyoming) were coded as 0 and all other states were coded as 1. Vegetable production acres per county (USDA ERS, 2014) were divided by the total farm land per county prior to analysis (USDA NASS, 2014).

The market variables analyzed were indicators of the strength of the food system before the advent of the NRCS high tunnel program. The specific, local food system factors examined were the percent of direct-to-consumer sales compared to total agricultural sales in 2007 (USDA ERS, 2014), the number of farmers markets per thousand people in 2009 (USDA ERS, 2014), and the percent of farms with community supported agriculture (CSA) programs in 2007 (USDA ERS, 2014). Direct-to-consumer sales include the total agricultural sales directly to individuals via farm stands, farmers markets, CSAs, or U-pick operations (USDA ERS, 2014; Low and Vogel, 2011). Median household income in 2010 was used in the analysis as an indicator of consumer buying power, and the percentage of people with low access to food in 2010 (USDA ERS, 2014) was included as an indicator of food insecurity. According to the USDA definition, households within one mile (1.6 km) of a grocery store have good access to food in urban areas; in rural areas, that distance is increased to 20 miles or 32 km (USDA ERS, 2014).

The socio-demographic factors analyzed included characteristics of county and farmer populations. Specific characteristics of the county populations examined were the percentage of the total population composed of minority individuals (U.S. Census Bureau, 2014), urbanization as measured by the Rural Urban Continuum Code (RUCC), and the percentage of the population voting for the Democratic candidate in the 2012 presidential election (U.S. Geological Survey, n.d.). Specific characteristics of the farmer populations included the percentage of non-white (USDA NASS, 2014) and beginning farmers (USDA NASS, 2014). RUCC values range from one to nine and were developed by USDA to characterize counties by their degree of urbanization and proximity to metropolitan centers (USDA ERS, 2013). Counties with an RUCC value of 3 (i.e., metropolitan counties with fewer than 250,000 people) or 4 (i.e., nonmetropolitan counties with an urban population of 20,000 or more, and adjacent to a metropolitan area) were coded as 1, and all other counties were coded as 0.

Farmer Survey

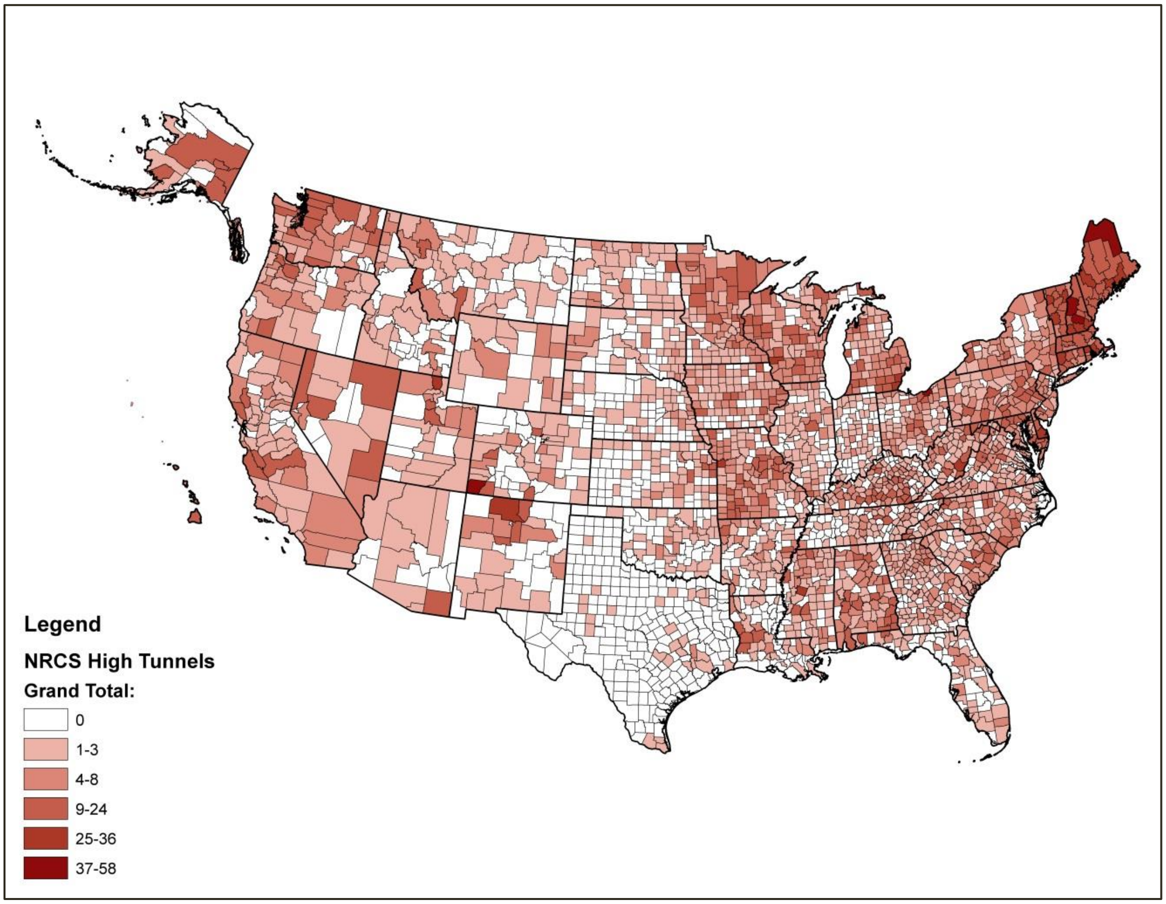
High tunnel growers in Virginia were surveyed to elicit details about their demographics, production practices, sales venues, revenue, and satisfaction with the NRCS high tunnel program. Our survey contained 13 questions and was distributed using email lists via Virginia Cooperative Extension, the Virginia Association for Biological Farming, the Catawaba Sustainability Center (Catawaba, Virginia), and the Local Food Hub (Charlottesville, Virginia). Responses were collected by VT Survey (survey.vt.edu), facilitated by Virginia Tech. After receiving approval from the Institutional Review Board at Virginia Tech (IRB #10-1377), an email soliciting survey participation was distributed in April 2014 and was followed by a second email solicitation two months later. Survey responses could have potentially suppressed responses from those who do not have internet access due to the Internet-based survey collection method or affiliations with the survey distribution outlets specified above.

Results

GIS High Tunnel Mapping

Between January 2010 and December 2013, the NRCS high tunnel program (USDA, 2013) provided cost-share to qualifying growers for the construction of 9,489 high tunnels. Under the program, 1,810 high tunnels were contracted in 2010, 1,638 in 2011, 3,043 in 2012, and 2,998 in 2013. Assuming an average size of 2,000 ft^2 (186 m^2) per high tunnel (UIE, 2014), these high tunnels cover roughly 436 acres (176 ha) (0.027% of total harvested vegetable acreage in the U.S.) (USDA NASS, 2014). The states that adopted the most NRCS high tunnels were Alaska (513), Missouri (480), and Michigan (408); the states that adopted the least were Nevada (5), Arizona (22), and Wyoming (31). Mapping shows that NRCS high tunnels are not uniformly distributed throughout the U.S. (Figure 1a).

Figure 1a. Number of NRCS High Tunnels in the United States Funded January 2010–December 2013 by County



Note: Alaska and Hawaii are not to scale.

Regression Analysis

Biophysical factors showed the strongest relationship with NRCS high tunnel adoption compared to market and socio-demographic factors (Table 1). Latitude was the strongest predictor of NRCS high tunnel adoption in the U.S.; counties at higher latitudes adopted more NRCS high tunnels than counties at lower latitudes. States outside the arid Midwest were more likely to adopt NRCS high tunnels than states inside it. Average farm size was negatively correlated with the number of NRCS high tunnels per county, meaning that NRCS high tunnels are more abundant in counties with a higher proportion of small farms. Additionally, NRCS high tunnel numbers increased with increasing amounts of land used for field vegetable production (Table 1).

Market variables also influenced NRCS high tunnel adoption. As the median household

income increased in a county, so did the number of NRCS high tunnels (Table 1). Furthermore, NRCS high tunnel adoption occurred where there were already relatively robust food systems. Where there was good access to grocery stores, NRCS high tunnel adoption was high (USDA ERS, 2014). Where direct-to-consumer sales were high in 2007, NRCS high tunnel adoption was also high. However, farmers markets and CSAs per county were not specifically related, individually, to NRCS high tunnel adoption.
Two significant relationships were found between NRCS high tunnels and the socio-demographic factors examined (Table 1). A growing non-white population in a county was related to increased NRCS high tunnel adoption. Additionally, more high tunnels were adopted in small metropolitan counties (population fewer than 250,000 people) or large urban counties (population greater than 50,000 people) than in other places. There was no significant correlation between NRCS high tunnel adoption and Democratic votes in the 2012 presidential election. Furthermore, there was no significant relationship between NRCS high tunnels per county and the percentage of non-white or beginning farmers (Table 1).

Table 1. Negative Binomial Regression - Relationships Between NRCS High Tunnel Adoption and Biophysical, Market, and Socio-demographic Variables[5]

	Variable	**Estimate**	***p*-value**[a]
Biophysical	Latitude [b]	9.06e-02	< 0.0001
	Outside the arid Midwest [c]	5.61e-01	< 0.0001
	Average farm size (acres) (2007)[d]	-1.24e-04	<0.0001
	Vegetable production (acres)[d]	7.80e-05	< 0.01
Market	Direct-to-consumer sales (%) (2007)[e]	4.33e-02	<0.0001
	Median household income (2010)[e]	4.60e-06	<0.01
	Food access (% of total population) (2010)[e]	2.86e-03	<0.01
	CSAs (% of total farms) (2007)[e]	5.17e-01	0.09
	Farmers markets (# per 1,000 people) (2009)[e]	1.26e-01	0.74
Socio-demographic	Non-white population (%) (2010)[b]	4.14e-03	<0.0001
	RUCC [f, g]	1.77e-01	<0.001
	Democratic votes (%) (2012)[h]	2.17e-03	0.21
	Non-white farmers (%) (2007)[d]	-1.33e-03	0.32
	Beginning farmers (%) (2007)[d]	-2.81e+00	0.19

[a] *p*-values ≤0.01 are considered significant.
[b] U.S. Census Bureau, 2014
[c] States were assigned the following codes:
0. Arid Midwest: AZ, CO, ID, KS, MT, NB, NV, NM, ND, OK, SD, TX, UT, WY
1. Outside arid Midwest: All other states
[d] USDA, 2009; [e] USDA ERS, 2014; [f] USDA ERS, 2013
[g] Rural Urban Continuum Codes (RUCC) (USDA, ERS, 2013). Counties with a RUCC of 3 or 4 were aggregated and coded as 1. All other counties were coded as 0.
[h] U.S. Geological Survey, n.d.

Farmer Survey

[5] R-square regression code can be found in Appendix C.

Sixty-five Virginia high tunnel growers participated in our survey, which included both farmers who did (*n*=47) and did not (*n*=18) participate in the NRCS high tunnel program. All together, these farmers managed 142 high tunnels (47 NRCS and 95 other high tunnels). While the total number of high tunnel producers in Virginia is unknown, our survey captured 15% of Virginia's 314 NRCS high tunnel recipients.

The surveyed high tunnel farmers answered questions about their demographics, growing practices, and sales venues, with results presented in Table 2. Survey participants reported their race as white (92%), black (3%), Hispanic (2%), or did not disclose their race (3%). The gender of participants was 41% female, 56% male, and 3% undisclosed. Forty-six percent of respondents reported using their high tunnel(s) for year-round production, and 54% use them throughout spring, summer, and fall. Respondents reported growing a wide variety of produce in their high tunnels; all grew vegetables, fruit, or both, and 65% also grew herbs and/or cut flowers. Survey responses strongly support the presumption that NRCS high tunnels contribute to local food availability. Of the 65 respondents, 82% sold the majority of their product (at least 75%) within 50 miles (80 km) of their farm. All respondents also reported selling through direct-to-consumer venues, with farmers markets being the most popular venue.

The NRCS high tunnel program increased the willingness of farmers in Virginia to purchase future high tunnels. Forty-four percent of NRCS high tunnel recipients would, and 66% would not, have built their NRCS high tunnel without the cost-share program. After using the NRCS high tunnel, 56% of survey respondents indicated that they are likely or very likely to purchase another high tunnel without a subsidy, while only 21% were not likely. Twenty-three percent of survey participants were undecided about purchasing a future high tunnel. All the farmers who reported generating more than US$2,000 per high tunnel per year of revenue were likely or very likely to purchase a future high tunnel without government support.

Table 2 Virginia High Tunnel Growers Survey (n =65, except where noted)

Demographics		
1. What is your age?	**2. What is your gender?**	**3. What is your ethnicity?**
Average: 50	Male: 56%	White (non-Hispanic): 92%
Minimum: 23	Female: 41%	Black: 3%
Maximum: 72	No answer: 3%	No answer: 3%
Respondents < 50: 37%		Hispanic: 2%
		Asian or Native American: 0%

Production			
4. How many high tunnels do you have on your farm?	**5. How many total square feet of high tunnel production do you have on your farm?**	**6. What do you grow in your high tunnel(s)? ***	**7. Which season(s) do you use your high tunnel for production? ***

Average: 2.27	Average: 4,595 sq. ft.	Veggies: 92%	Winter: 65%
Minimum: 1	Minimum: 260 sq. ft.	Fruit: 25%	Spring: 97%
Maximum: 12	Maximum: 32,000 sq. ft.	Herbs: 38%	Summer: 83%
		Flowers: 27%	Fall: 90%

Marketing

9. Please indicate your marketing strategy(s).*	**10. Please indicate the type(s) of direct market venues you use.***	**8. How many miles from your farm to the market(s) is 75% or more of your high tunnel produce sold?**
Direct-to-consumer/ restaurant/food hub:100%	Farmers market: 71% Direct-to-restaurant: 38%	50 miles or less: 82% 51 to 100 miles: 13%
Wholesale: 14%	CSA: 32%	101 to 150 miles: 3%
	Roadside stand: 24%	151 to 200 miles: 0%
	On-farm stand: 20%	More than 201 miles: 2%
	Pick-your-own: 8%	
	Other: 4%	

Economics

11. Please select the range that best describes your annual revenue per high tunnel (*n*=21).^	**12. Would you have constructed a high tunnel without NRCS funding (*n*=44)?**	**13. If you participated in the NRCS high tunnel program, please rank how likely you are to purchase a future high tunnel without NRCS funding (*n*=47).**
$0 - 500: 14%	No: 66%	Not likely: 15%
$501 - 2,000: 33%	Yes: 34%	Less than likely: 6%
$2,001 - $3,000: 19%		Undecided: 24%
>$3,000: 10%		Likely: 23%
I do not know: 24%		Very likely: 32%

*** Respondents could select multiple options**
^ Excludes data from respondents who did not participate in the NRCS high tunnel program and who had more than 1 high tunnel.

Discussion

Farmers

The strongest determining factors in the distribution of NRCS high tunnels are biophysical (Table 1). Not surprisingly, farmers at high latitudes are taking advantage of high tunnels because they can extend the growing season in cold climates (Figure 1; Smeenk & Nakazawa, 2011). Farmers outside of the arid Midwest also adopted high tunnels at higher rates than in landlocked states with hot, dry climates. Most farms in the arid Midwest are large, distant from metropolitan areas, and have little existing vegetable production. These factors are all significantly related to high tunnel adoption, according to our analysis (Table 1) (Low & Vogel, 2011).

High tunnels may present an opportunity for small-scale vegetable farmers (less than US$10,000 annual revenue) to grow their operations (Table 1). While globalization of the food system tends to favor large-scale operations (Jensen, 2010), many large farms depend on uniformity in management. High tunnels, on the other hand, require more nuanced management and labor that cannot be performed mechanically, and therefore may be better suited to use on small farms (Biernbaum, 2013). Furthermore, many small farms suffer from a lack of credit and an erratic flow of income (Dodson & Koenig, 1995). Our survey results show that farmers in Virginia are using high tunnels to extend their growing season, year-round in some places, which can increase total sales and stabilize income throughout the year (Table 2). As a bonus, high tunnel growers are also likely to receive premium prices for out-of-season, local produce (Arnold & Arnold, 2003; Lamont et al., 2002; Orzolek, 2013).

The NRCS high tunnel program was intended to benefit historically underserved farm operators (USDA NRCS, 2014; National Sustainable Agriculture Coalition [NSAC], 2014). Table 1 indicates that adoption of NRCS high tunnels is positively related to the percentage of the population that is non-white. However, there is no correlation between the percentage of non-white farmers or beginning farmers and the presence of NRCS high tunnels in a given county. On the other hand, analyses by NSAC show that underserved, and particularly beginning farmers, have enrolled in the NRCS high tunnel program at higher rates than non-underserved farmers (NSAC, 2014). Indeed, more than 70% of NRCS high tunnel contracts were awarded to historically underserved operators in 2013 (NSAC, 2014). While the NSAC analysis examined only data about NRCS high tunnel recipients, our data describe the underserved farmer populations of entire counties. Therefore, our data indicate that counties with high proportions of underserved farmers were not more successful than counties traditionally well-served by the USDA in obtaining NRCS high tunnel contracts.

Our survey conducted with farmers in Virginia indicates that high tunnels may particularly benefit female farmers (Table 2), which is encouraging in a traditionally male-dominated global food system (Trauger, 2004). When asked to identify their gender, 41% of surveyed high tunnel growers (n=65) identified as female principal operators. This is in contrast to national averages reporting females are principal operators of only 14% of all farms, 12% of vegetable farms, and 17% of small farms (USDA NASS, 2014). Most female farmers can be found in the west and northeast (USDA NASS, 2010), which is also where many of the NRCS high tunnels are located (Figure 1).

Consumers

This research highlights the possibility that consumers who lack access to grocery stores and are low-income may not be benefitting from the additional produce grown in NRCS high tunnels (Colasanti, Conner, & Smalley, 2010, Table 1; Hill, Wishaw, & Hargrove, 2013). In Virginia the survey responses indicate that high tunnels contribute more to local than to global markets. Our national data further indicate that NRCS high tunnel adoption increased in or near small metropolitan counties with high incomes and easy access to grocery stores (Table 1). Therefore we can conclude that NRCS high tunnels may be doing little to alleviate food deserts or to provide fresh, locally grown food to low income-communities. In fact, they may be contributing to a problem with the local food system that many people criticize, namely, that it primarily serves upper-income, urban communities (Alkon & McCullen, 2011; Campbell, Carlisle-Cummins, & Feenstra, 2013; Johnston & Baker, 2005).

Local Food Movement

There may be a positive feedback between a strong local food market, the adoption of high tunnels, and the continued growth of that market (Sundkvist, Milestad, & Jansson, 2005). Our data show that direct-to-consumer sales in 2007 were highly correlated with consequent adoption of NRCS high tunnels (Table 1). In Virginia, high tunnel produce was sold primarily within 100 miles (161 km) of where it was grown. This is well within the limits of USDA's definition of local (400 miles, or 644 km) (Martinez et al., 2010). The adoption of new technologies does not occur in a vacuum (Adler, Fung, Huber, & Young, 2003). Farmers looking to enter local food markets may be finding success selling their high tunnel produce where the local food market is already strong.

High tunnels appear to be an emerging technology that will continue to contribute to the local food movement (Martinez et al., 2010). Our survey of Virginia farmers indicates that farmers find high tunnel technology profitable and are willing to purchase new high tunnels even without further government subsidies. Growing food in high tunnels is much more common in other countries, such as China, Spain, Japan, and Italy (Lamont, 2009). In 2007, before the advent of the NRCS high tunnel program, Carey et al. (2009) estimated that there were only 5,000 acres (2,023 ha) of high tunnel production in the U.S. (0.01% of total vegetable production acreage). Reasons for relatively low use of high tunnels and other protected production methods in the U.S. could include low transportation costs and highly centralized marketing systems. These tend to favor large-scale farms that supply cheap, but potentially lower quality, produce than food produced locally (Edwards-Jones et al., 2008).

Conclusions

High tunnels are a promising technology that can increase farmers' profits (Arnold & Arnold, 2003; Chase, 2012), supply fresh and healthy produce to consumers, and fuel growth in the local food movement (ATTRA, 2009). They can also fill a niche for out-of-season local foods that is unlikely to be filled by large-scale producers growing for the global food system (Biernbaum, 2013). As with many newly adopted technologies, high tunnels may be a double-edged sword. While many hope that they will equitably increase local food supplies and food security, our data show that the NRCS high tunnel program was not particularly successful in counties with low incomes or large, underserved farmer populations. Furthermore, those counties that already had diverse food choices now have even more choices because of U.S. government support. Future research efforts should continue to investigate the impacts of high tunnels on food deserts, poor communities, and underserved farm operators.

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MANUSCRIPT 2

Assessing the conservation value of high tunnel cucumber and tomato production

Abstract

The Natural Resource Conservation Service (NRCS) makes several claims about the conservation value of high tunnels including that they improve plant quality and reduce pesticide use. However, these conservation claims remain largely unquantified. In this study, we compare pest and disease pressure, yield, and the number of pesticide applications on cucumbers (*Cucumis sativus*) and tomatoes (*Solanum lycopersicum*) grown in high tunnels and in open field cultivation. We also surveyed farmers' perceptions about high tunnel impacts on pests and pesticide use. Cucumbers grown in high tunnels experienced lower striped cucumber beetle (*Acalymma vittatum*) populations but similar levels of bacterial wilt (*Erwinia tracheiphila*) compared to those grown in the field. Tomatoes grown in high tunnels showed lower late blight (*Phytophthora infestans*) and botrytis (*Botrytis cinerea*) disease pressure, similar levels of sooty mold (*Alternaria* alternate) and early blight (*Alternaria* solani), and higher aphid populations than tomatoes grown in the field. The number of pesticide applications on cucumbers was similar in high tunnels and the field, whereas the number of pesticide applications on tomatoes was higher in high tunnels than in the field. Both cucumbers and tomatoes yielded more and yield per pesticide application was also significantly higher in high tunnels than in the field. This is in contrast to farmers' perceptions that high tunnels reduce both pests and pesticide use. These results show that high tunnels may not always reduce pest and disease pressures and may even result in more pesticide use than in field cultivation. However, high tunnels can provide conservation benefits by increasing production per unit of pesticide input.

Introduction

Traditionally, vegetable production has been concentrated in regions of the U.S far from most consumers (Drabenstott, 1999). More recently, there is an emerging trend that consumers are demanding high quality fruits and vegetables grown locally (Low and Vogel, 2011; Martinez, 2010; Low, 2015). However, the availability of locally grown produce is limited by climate, especially at higher latitudes (Hood, Little, Coatney, & Morgan 2011; O'Connell, Rivard, Harlow, Peet, & Louws, 2012).

High tunnel production is one way to increase the amount of local produce available in direct-to-consumer markets (Anderson, 2007; Boys, 2013; Gillespie, 2007). While high tunnel technology has been used for over 70 years in the U.S., the number of high tunnels has increased rapidly in recent years (Jett, 2004; Lamont, 2005; Carey, 2009). In addition to the growing demand for local produce, the U.S. Department of Agriculture (USDA) has played an important role in promoting high tunnel adoption. In 2010, the USDA Natural Resource Conservation Service (NRCS) began the seasonal high tunnel (SHT) cost-share program to support high tunnel construction. Since then, NRCS has supported the construction of over 9,489 high tunnels in the U.S. (Foust-Meyer and O'Rourke, 2015).

The NRCS high tunnel program was designed as a conservation effort aiming to increase plant quality, reduce pesticide use, and increase the availability of local produce (NRCS, 2014). However, the ability of high tunnels to fulfil these conservation goals is unclear. To date, research on high tunnel production has mostly focused on improving methods of production (Orzolek, 2013; Jett, n.d.; Lamont, 2012; O'Connell, 2012).

Studies examining the impacts of high tunnels on plant quality impacts from pests show mixed results. Lamont (2005) found that there was decreased incidence of disease in high tunnels compared to open field production. High tunnel production of heirloom and hybrid tomatoes has also been shown to lower disease incidence of rain-vectored disease compared to those grown in the field (Hood, 2012; Lamont, 2005; Rogers and Wszelaki, 2012). However, it has also been reported that high tunnels can lead to increased levels of diseases, such as powdery mildew (*Sphaerotheca fuliginea*), botrytis (*Botryotinia cinerea*), and tobacco mosaic virus (Pullano, 2015). Pests such as tomato hornworm (*Manduca quinquemaculata*), cutworm (*Agrotis* sp.), thrips (Thysanoptera), and various types of aphids (Aphideae) can also be abundant in high tunnels (Everhart, 2010; Pullano, 2015).

Understanding the biology of different pests and how high tunnels change environmental growing conditions can help to predict how high tunnels will affect pest pressures and pesticide use. High tunnels exclude rain and can, therefore, reduce diseases vectored by rain and spread by soil splashing on leaves during ran storms. On the other hand, high tunnels can create a favorable environment for overwintering pests (e.g. aphids, tomato hornworm, striped cucumber beetle (SCB) and disease (e.g. early blight, tobacco mosaic virus) if crop residues are not properly removed (Thomas, 2012). The high temperatures and frequently high humidity in high tunnels can also accelerate disease and insect development (Snyder, Ballard, Yang, Clevenger, Miller, Ahn, Hatten, Berryman, 2004). The presumption is that if high tunnels reduce pest pressures, they will reduce pesticide use. However, there have been no studies directly comparing pest and disease pressures and pesticide use in high tunnels and field conditions.

This study aims to investigate the proposed conservation benefits of the NRCS high tunnel program, including impacts of high tunnel production on plant quality and pesticide use. We studied cucumber (*Cucumis sativus*) and tomato (*Solanum lycopersicum*) because they are frequently cited as two of the most profitable high tunnel crops (Coltrane and Jett, 2004; Butler and Bauer, 2013). We specifically address the following questions. Do high tunnels increase plant quality by reducing insect pest and disease pressures? Are fewer pesticides needed in high tunnel than field production of crops? What are farmers' perceptions of high tunnel impacts on pest pressure?

Materials and methods

Crop disease and insect pressure

Our experiment was conducted on 7 vegetable farms located throughout the state of Virginia between USDA growing zones 6 and 7. Growers were identified through solicitations to Virginia Cooperative Extension, the Virginia Association for Biological Farming 2014 conference, and the Local Food Hub (Charlottesville, Virginia). Field observations and data were collected from farms with both high tunnel and open field production. Each farm was visited once every two weeks during the 2014 growing season from planting until death. All farms had 5 cucumber plants and 5 tomato plants of the same variety planted inside and outside their high tunnels.

Each farm was given Corinto cucumber transplants, an indeterminate variety well suited to high tunnel, greenhouse, or field production. In order to match farmer demands for specific tomatoes, 4 indeterminate varieties were selected (Sakura honey, Sungold, Striped German, and Big Beef). Transplants were started under 12 hours of fluorescent light for 4 weeks, in 72-cell trays (55 cc/cell) containing fine germination media (Faffard, Millerton, NY). After 4 weeks, tomatoes were repotted into 4 inch square pots with Faffard 3b potting mix (Faffard brand, Millerton, NY). High tunnel tomato seeds were started in late January/early February. Field tomatoes and high tunnel cucumber seeds were started in late February. Field cucumber seeds were started in mid-March. Transplants were delivered to farms 2 weeks before planting when plants had 4 to 6 true leaves and Sungold variety tomatoes had 1 to 2 flowers at the time of delivery. All plants were acclimated in partial shade with daily watering for a minimum of 10 days before transplanting. Planting dates varied between farms and treatments. High tunnel cucumbers were planted between 4/25/2014 and 6/2/2014 and were terminated between 7/10/2014 and 8/23/2014; field grown cucumbers and tomatoes were planted between 5/5/2014 and 5/20/2014 and were terminated between 7/18/2014 and 8/18/2014. High tunnel tomatoes were planted between 4/24/2014 and 5/5/2014 and were terminated between and were terminated between 7/7/2014 and 7/23/2014.

On each farm, plants were given the same fertilizer, water, mulching and/or pruning inside and outside of the high tunnel based on the farmers' preferred management strategies. Each farm used drip irrigation in both high tunnel and open field production. Pesticides were applied at the discretion of the individual farmer. Frequency and amount of pesticide applied were self-reported by each farm. Marketable yields were recorded by each farmer. Differences in planting dates and cultivars in tomato lead to varied harvest dates on each farm. The harvest began once the participating farmer was satisfied with fruit size, quality and ripeness.

Each plant (10 cucumbers and 10 tomatoes per farm) was scouted for pests and disease once every two weeks. The entire plant was scouted to determine SCB populations. Assessment of aphid populations consisted of counting the number of aphids on the upper canopy leaf and an interior, lower canopy leaf (inner leaf). The upper leaf was the leaf below the highest open flower on the plant. The inner leaf was the fifth leaf below the highest open flower (Pedigo, 1994, Hummel et al., 2004). Disease severity was assessed based on a scale of 0 – 5 (0 meaning no herbivory or infection; 5 being plant death) (Edwards, 2010). Samples of the observed pests were collected and analyzed at the

Virginia Tech Insect Identification Lab and diseases were confirmed with samples sent to the Virginia Tech Plant Disease Clinic (Blacksburg, VA).

Grower survey

In addition to field observations, 60 high tunnel growers in Virginia were surveyed to determine their perception of pest and disease pressures on their farms and in their high tunnel(s). Six of the seven on-farm research participants also responded to the survey. Each of the Survey respondents had at least one year of experience growing in high tunnels. Survey respondents were asked to rate their farms insect and disease pressure (1 = no pressure; 2 = some pressure; 3 = moderate pressure; 4 = severe pressure; and 5 = very severe pressure).

The survey was approved by the Institutional Review Board at Virginia Tech (IRB #10-1377). Surveys were distributed via email lists from Virginia Cooperative Extension, the Virginia Association for Biological Farming, the Catawaba Sustainability Center (Catawaba, Virginia), and the Local Food Hub (Charlottesville, Virginia). Responses were collected by VT Survey (survey.vt.edu) administered by Virginia Tech. An initial email soliciting farmer responses was distributed April 2014, followed by a second email in June 2014.

Data Analysis

Statistical calculations were analyzed using JMP 11 (SAS Institute Inc., 2013). Significant statistical differences between treatments were determined at $P < 0.050$. SCB and aphid populations were analyzed using the mixed model function to execute a repeated measures ANOVA. In the model, the high tunnel or field treatment was a fixed variable, the farm site was a random variable, and time including 5 weeks of measurements was a repeated measure variable. Disease severity, yield, and yield per pesticide application were analyzed using ANOVA blocked by farm with all measurements averaged per plant and over time before analysis. The response variables in the pesticide and yield analyses were the sum per plant over the entire year of all harvested fruit or the number of times a pesticide was applied, respectively. Yield (kg) per pesticide application was determined by dividing total yield per plant by the total number of pesticide applications including all the different types of pesticides applied to cucumbers or tomatoes.

Results

Pest and disease pressure

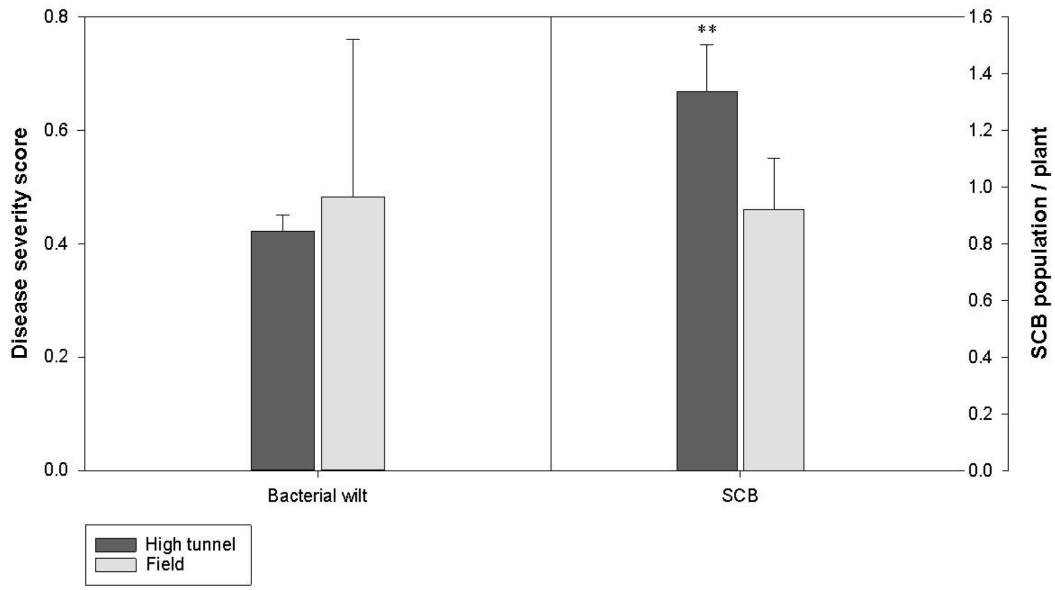

Figure 1. SCB populations and disease severity scores on cucumbers. Observations of five high tunnel planted and five field planted cucumbers. Disease severity was assessed based on a scale of 0 – 5 (0 meaning no infection; 5 being plant death). SCB populations were directly counted and averaged ($P = 0.0013$). One asterisk (*) indicates a significance level < 0.05, two asterisks (**) indicate a significance < 0.01, and three asterisks (***) indicate a significance level < 0.001.

SCB populations were higher in high tunnels than in the field SCB ($P = 0.0013$). However, bacterial wilt (*Erwinia tracheiphila*) severity, a disease vectored by SCBs, was similar in both high tunnel and in the field grown cucumbers ($P = 0.2247$). Powdery mildew levels were insignificant on sampled plants both inside and outside high tunnels. Scouting efforts also revealed very low populations of cutworms (Noctuidae) and spotted cucumber beetles (*Diabrotica undecimpunctata howardi*) on cucumbers.

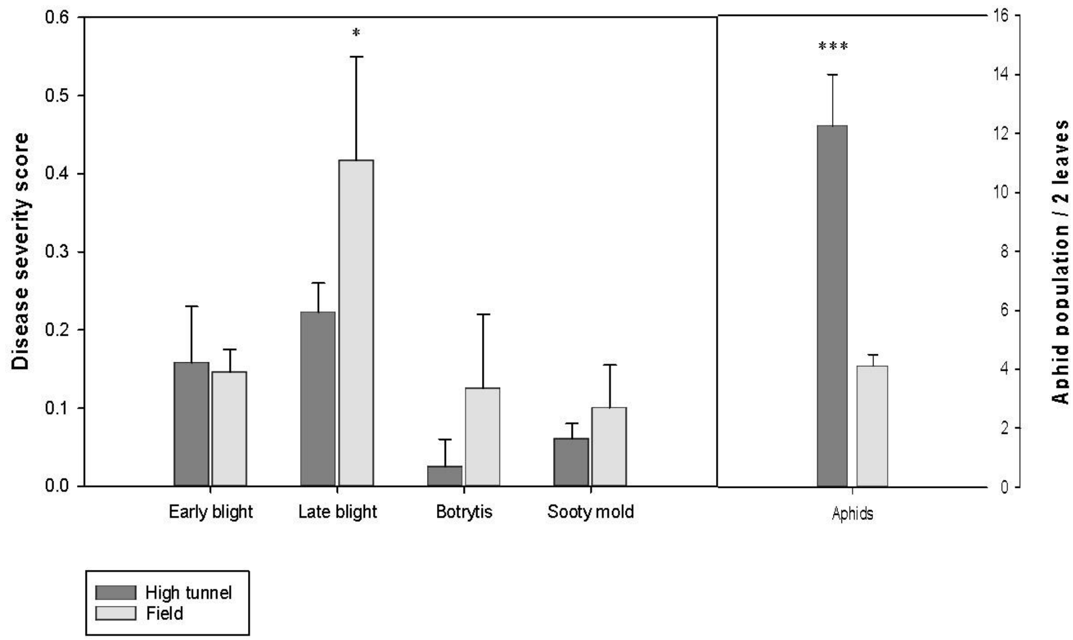

Figure 2. Aphid and disease severity scores on tomatoes. Observations of five high tunnel planted and five field planted tomatoes. Disease severity was assessed based on a scale of 0 – 5 (0 meaning no infection; 5 being plant death. To assess aphid populations the number of aphids on the upper canopy leaf and an interior, lower canopy leaf (inner leaf) were totaled. The upper leaf was the leaf below the highest open flower on the plant. The inner leaf was the fifth leaf below the highest open flower. (P = <0.0001). One asterisk (*) indicates a significance level < 0.05, two asterisks (**) indicate a significance < 0.01, and three asterisks (***) indicate a significance level < 0.001.

Disease severity was assessed on over each plant based on a scale of 0 – 5 (0 meaning no infection; 5 being plant death) (Edwards, 2010). Relationships between high tunnels and tomato pests varied depending on the specific pest organism. Tomatoes planted in the high tunnel had significantly higher aphid (Aphididae) populations than those in the field (P = <0.0001) (Figure 2). Scouting efforts revealed very low populations of tomato hornworm (*Manduca quinquemaculata*) on tomatoes. Sooty mold (*Alternaria* alternate), which grows on the secretions of aphids, was not statistically different on tomatoes inside and outside of high tunnels (P = 0.3694). Early blight (*Alternaria solani*) was also equally severe inside and outside of high tunnels (P = 0.7452). In contrast, late blight (*Phytophthora infestans*) (P = 0.0474) and botrytis (*Botrytis cinerea*) (P = 0.0001) diseases in tomatoes were both significantly more severe on field grown plants than those grown in the high tunnel (Figure 2).

Pesticide applications and crop yield

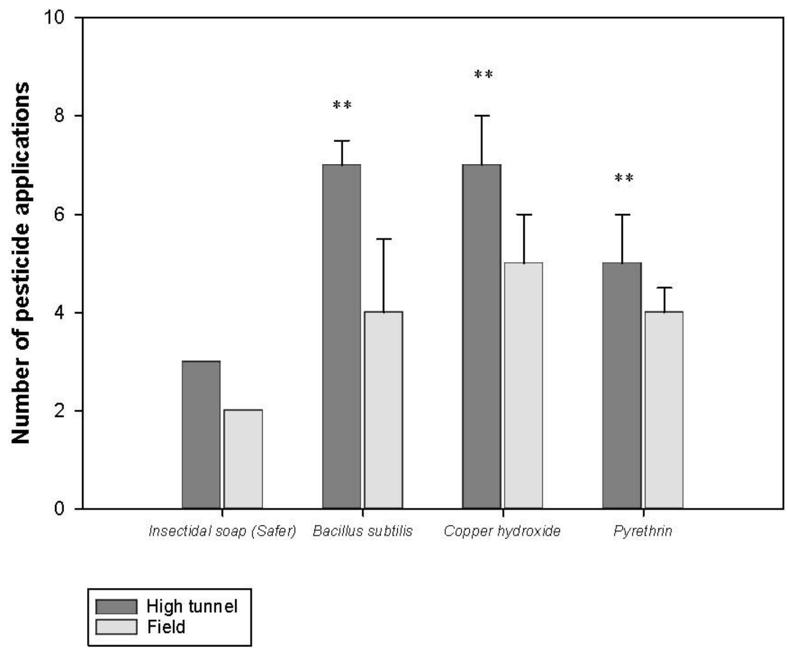

Figure 3. Total number of pesticide applications. The number of pesticide applications was self-reported by individual farmers, who applied pesticides independently. Observations of five high tunnel planted and five field planted cucumbers and tomatoes. After the initial application pesticides were applied regularly every-other week. There was no statistical difference in the number of pesticide applications between high tunnel and field planted cucumbers (P = 0.2718). High tunnel grown tomatoes received a significantly more pesticide applications (P = 0.0019). One asterisk (*) indicates a significance level < 0.05, two asterisks (**) indicate a significance < 0.01, and three asterisks (***) indicate a significance level < 0.001.

Pesticide applications took place on a regular basis, every-other week. Farmers tended to use more pesticides inside high tunnels than in the field. Five farmers attempted to control SCB pressure with applications of pyrethrum extract in roughly equal amounts on both high tunnel and field planted cucumbers (P = 0.2718). Pyrethrum extract was applied to high tunnel cucumbers for an average of 5.17 weeks and 3.67 weeks on field planted cucumbers. In contrast, high tunnel planted tomatoes received a significantly higher number of pesticide applications than field planted tomatoes (P = 0.0019). Pesticides on tomatoes included an insecticide and two fungicides. Only one farm applied insecticide to their tomato crop (insecticidal soap) to help reduce aphid pressure, but did not apply fungicide. The insecticidal soap was applied for 6 weeks in both high tunnel and field tomatoes. The remaining farms applied either copper fungicides (active ingredient copper hydroxide) or *Bacillus subtilis*, a biofungicide used to reduce fungal pathogens on tomato plants. Both *Bacillus subtilis* (P = 0.0015) and copper hydroxide (P = 0.0314) were applied in greater amounts on high tunnel tomatoes than on the field tomatoes. Applications were made for an average of 5.75 weeks on high tunnel tomatoes and 4.6 weeks on field tomatoes (Figure 3).

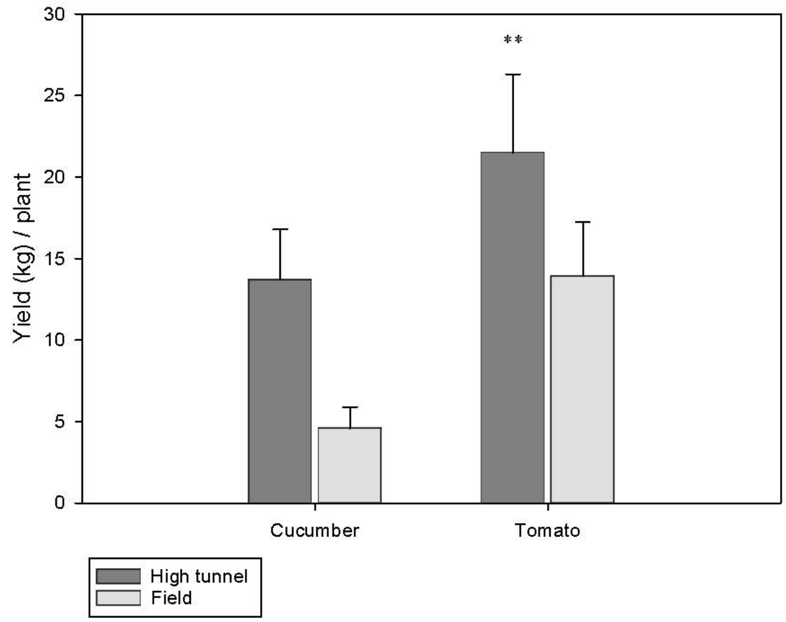

Figure 4. Total marketable yield (TMY) (kg). TMY was averaged over each farm, was self-reported by each farmer based on their individual standards of marketability. High tunnel grown cucumbers (*P* = 0.0192) and tomatoes (*P* = 0.0197) had significantly higher yields than those grown in the field. One asterisk (*) indicates a significance level < 0.05, two asterisks (**) indicate a significance < 0.01, and three asterisks (***) indicate a significance level < 0.001.

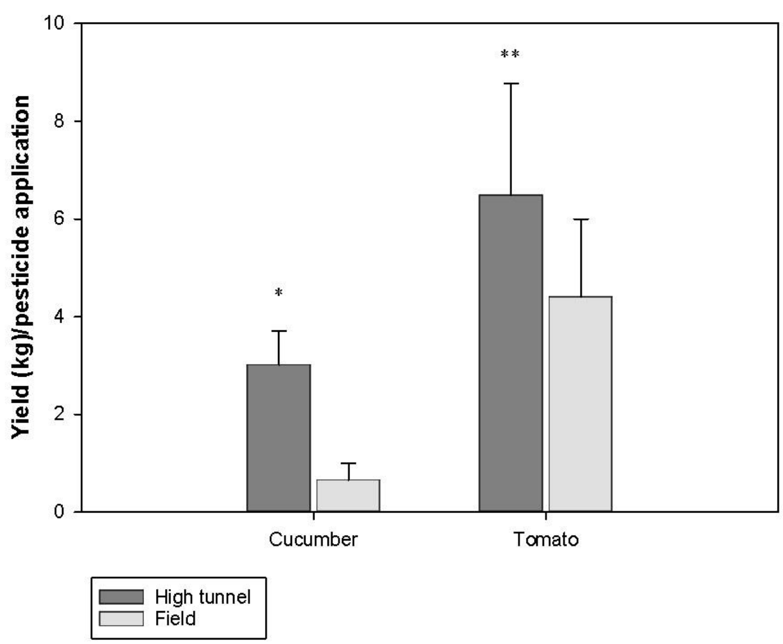

Figure 5. Total marketable yield (kg) per total number of pesticide applications. TMY was averaged over each farm and divided by the average number of pesticide

applications. Observations of five high tunnel planted and five field planted cucumbers and tomatoes. High tunnel production increased crop yield per number of pesticide applications in cucumber ($P = 0.0204$) and in tomato ($P = 0.0068$). One asterisk (*) indicates a significance level < 0.05, two asterisks (**) indicate a significance < 0.01, and three asterisks (***) indicate a significance level < 0.001.

Both high tunnel grown cucumbers ($P = 0.0192$) and tomatoes ($P = 0.0197$) had higher yields than those grown in the field (Figure 4). Results reported in Figure 4 were averaged over each farm. High tunnel grown cucumbers yielded 133 kilograms of marketable fruit. Field grown cucumbers yielded 34.5 kg of marketable fruit. High tunnel tomatoes (yield = 135.89 kg) also out produced field grown tomatoes (yield = 26.15 kg). The harvest period of tomatoes and cucumbers varied between farms. The average harvest period for field grown cucumbers was 6.43 weeks and 6.86 weeks for high tunnel grown cucumbers. Field grown tomatoes had an average harvest period of 3.86 weeks. High tunnel grown tomatoes had an average harvest period of 9 weeks. High tunnel production increased crop yield per number of pesticide applications in cucumber ($P = 0.0204$) and in tomato ($P = 0.0068$) (Figure 5).

Farmer perception of high tunnel and field pest and disease pressure

In our survey of Virginia high tunnel farmers ($n = 60$), most respondents perceive pest and disease pressure to be lower in their high tunnels than in field production. Most respondents perceive both disease (43) and insect (33) pressure to be lower in the high tunnel than in the field. Only two growers perceived that disease pressure was higher and seven perceived that insect pressure was higher in their high tunnels than in their fields. The remaining growers did not think there was a difference between diseases (15) and insect pest (20) pressure in their high tunnel and field production. All six on-farm research cooperators who completed the survey indicated that they thought disease pressure was lower in their high tunnel than in the field. Five of the six farmer cooperators perceived insect pressure to be lower and one indicated there was no difference between high tunnel and field production.

Discussion

Pest and disease pressure

Our observations indicate that high tunnels do not necessarily lead to reductions in most insect or disease pressure. In fact, without proper management, high tunnels may exacerbate some pests such as aphids and striped cucumber beetles (Figures 1 & 2). This may be due to high temperatures in high tunnels relative to the field, which can increase the growth and reproductive rates of some pests (Eaton, 2009, Bailey, 2003). High tunnels may also create a protected overwintering habitat that can harbor pests and diseases (Seedbold and Bessin, 2014). This means that preemptive long-term pest and disease management is best in high tunnels. Eliminating crop residue and weeds between harvesting and planting may be an important tool for reducing the overwintering sites and alternative hosts of crop pests and diseases.

While most of the pests and diseases observed in this study were not reduced by high tunnels, late blight pressure was less severe on tomatoes grown in high tunnels than in the field (Figure 2). By excluding rainfall, high tunnels may reduce pressure from diseases such as late blight that are vectored by rain (Jett, 2004; Rogers and Wszelaki, 2012). Furthermore, high tunnels help to keep leaf surfaces dry, which can reduce infection and minimize the ability of late blight spores to disperse (Jesiolowski, Cebenko, and Martin, 2001).

Careful understanding of insect and disease life cycles can help predict crop pests that can be exacerbated or suppressed in high tunnel production relative to field production. Specific life cycle factors that helped to explain the impacts of high tunnel production on pests in this study included: high tunnel heat, preferred overwintering conditions, alternative hosts, and dispersal behaviors. Knowing which pests fall into which category can help farmers anticipate and reduce pest pressures in high tunnel crops preemptively. For example, early-spring and late-summer plantings of cucumbers in high tunnels may allow growers to avoid exposing cucumber plants to extreme heat, which can exacerbate bacterial wilt infection (Eaton, 2009). Another example, farms with alternate aphid hosts (lettuce, apricot trees, etc.), planted with the observed plants experienced generally higher aphid pressure.

Crop productivity and pesticide use

The earlier planting may have led to better establishment and higher yield in both high tunnel cucumbers and tomatoes than in those grown in the field (Figure 4). The higher yield in high tunnel grown cucumbers may be attributed to the earlier planting date, because both high tunnel and field planted cucumbers had similar harvest periods (4.86 weeks and 5.43 weeks, respectively). High tunnel grown tomatoes received more pesticide applications than those grown in the field (Figure 3). This may be because of the regular pesticide applications made by growers and the longer average harvest period (5.33 weeks) of the high tunnel grown tomatoes than field grown tomatoes (4.5 weeks).

High tunnels provide benefits that aid plant yield and may increase the effectiveness of applied pesticides. In high tunnels, late blight incidence in tomatoes may be reduced and the effectiveness of pesticides may increase because rain will not wash them away (Wells and Fischel, 2012). Additionally, precise control of the amount of water the plants receive may lead to a greater marketable yield by reducing fruit cracking and rot (O'Connell, 2012). Our results show that high tunnels increase the marketable yield and yield per pesticide application (Figures 4 & 5).

Our results do not confirm the conservation goals of the NRCS high tunnel program. No statistical difference was found between the number of pesticide applications made to field or high tunnel grown cucumbers. More pesticides were applied to high tunnel grown tomatoes than to field grown tomatoes (Figure 4); however, the higher yield (Figure 3) and higher yield dividend (Figure 5) in both cucumbers and tomatoes may increase the conservation value of growing both in high tunnels. Instead, our results lead us to propose a new conservation benefit of high tunnel production, that high tunnels reduce the amount of total pesticide required to ensure a good harvest. This benefit is most obvious in the yield per number of pesticide applications, which was significantly higher in both high tunnel grown cucumbers and tomatoes than in field grown cucumbers and tomatoes (Figure 5).

High tunnel growers' perception of pest and disease pressure

As we observed farmer's perceptions of pest and disease pressure in our survey of Virginia high tunnel growers, we concluded that farmers' perceptions can often contrast scientific reports and findings (Obopilea, Munthalia, Matilo, 2008). Six of the growers that participated in both the field observations and high tunnel grower surveys reported that pest pressure is lower in their open field production than in their high tunnels. Only one grower reported that pest pressure as equally severe in their high tunnel and field production. In contrast to respondents' perceptions, our findings show that high tunnel production does not lead to uniform reductions in pest pressure (Figure 1 & 2). Based on some of the benefits promised under the NRCS high tunnel program many high tunnel growers may be surprised about the build-up of pest and disease pressure (NRCS, 2014; Merrigan, 2010). Surprise may be due to the relative abundance of anecdotal evidence and reports that study the benefits of high tunnel production (Lamont, 2005; Orzolek, 2013; Jett, n.d.) and the lack of reports and peer-reviewed literature that describe its challenges.

Conclusions

Our study indicates that high tunnels can increase yields (Figure 4) and reduce the amount of pesticide applications needed per unit of yield (Figure 5) in high tunnel grown cucumbers and tomatoes. We observed a decrease in late blight severity on tomatoes (Figure 2). However, high tunnel technology is not a silver bullet for eliminating all pest and disease problems—despite some claims made by the NRCS (NRCS, 2014). Multiple long-term management strategies are necessary to maximize plant quality, minimize pesticide use, pest and disease pressure. Development and implementation of these strategies will require understanding the pest and disease life cycle factors we observed (sensitivity to heat, favorable overwintering conditions, alternative hosts, and dispersal behaviors of pests). Simply growing plants in high tunnels did not eliminate obstacles of production. However, high tunnels with minimal pest or disease pressure may increase crop yield and provide fresh produce over a greater portion of the year.

Our findings do not validate the current conservation goals of the NRCS high tunnel program. Instead, high tunnel production may meet our alternate conservation goals of increasing plant quality and increasing yield per pesticide application. More pesticide applications were applied to high tunnel grown cucumbers and tomatoes (Figure 3). However, the higher yield (Figure 4) and yield per pesticide application (Figure 5) in high tunnel grown plants justifies exploring new conservation benefits of high tunnel production.

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SUMMARY OF CONCLUSIONS

High tunnels and local food

High tunnels help supply local markets with fresh produce. High tunnel produce is likely to be sold on the direct-to-consumer level (Table 2) according to responses from Virginia high tunnel growers. However, high tunnels are not evenly distributed between social, demographic or economic lines (Table 1a). High tunnel produce production is most likely to be done by white farmers in their 50s on small acreage vegetable farms (Table 1a & 2). While high tunnel production benefits the local food movement, work remains to ensure that all demographics benefit from the produce grown in government subsidized high tunnels.

Our data show that the NRCS high tunnel program was not particularly successful in counties where demand for local food is low (Low and Vogel, 2012). These areas are most likely to have lower than average household incomes and/or large underserved farmer populations. Additionally, counties that already had high food access are likely to now have even more choices because of the NRCS high tunnel program. Future research and planning efforts should continue to investigate the impacts of high tunnels on food deserts, poor communities, and underserved farm operators.

High tunnel impacts on crop pests, disease, yield and pesticide use

High tunnel production of cucumber and tomato reveals mixed benefits to insect pest and disease pressure. Pest and disease pressure was not consistently lower in high tunnel grown plants (Figure 1b & 2). While more pesticide applications occurred in the high tunnels, the greater yield per pesticide application (Figure 5) justifies the pesticide use. However, this is not a conservation benefit that is explained by the NRCS.

To date, the literature describing the NRCS high tunnel program has indicated that high tunnels reduce total pesticide use (NRCS, 2014). This is not consistent with our findings. We find is that high tunnel production of cucumbers and tomatoes results in a greater yield per pesticide application. This leads to an overall increase in productivity and a reduction in the amount of pesticide needed to obtain that yield.

Conservation and sustainable food systems

Our results lead us to conclude that high tunnel produce is local produce that is likely to require fewer pesticide applications and offers greater selection to direct-to-consumer markets. The NRCS high tunnel program has not met all of its goals to assist underserved communities. However, it does fortify the conservation value of local food. By growing crops in high tunnels the availability of local produce is increased and so is the yield per pesticide application. High tunnel production does not provide a single answer to increasing the availability of local produce, reducing pest and disease pressure, or pesticide use. However, high tunnel production can be used as one tool among many to create a more sustainable food system.

Appendix – A. Copyright permission from the Journal of Agriculture Food Systems and Community Development

Appendix – B. IRB Approval Letter

Appendix – C. Table 2. R code.

```
Call:
glm.nb(formula = mu[, 1] ~ mu[, 2] + mu[, 3] + mu[, 4] + mu[,
    5] + mu[, 6] + mu[, 7] + mu[, 8] + mu[, 9] + mu[, 10] + mu[,
    11] + mu[, 12] + mu[, 13] + mu[, 14] + mu[, 15], data = mu,
    init.theta = 0.6732859, link = log)
```