Horticultural Crop Production in High Tunnels in the United States: A Snapshot

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ADDITIONAL INDEX WORDS. hoop house, protected agriculture, controlled environment agriculture, vegetable, fruit, flower

SUMMARY. High tunnels are becoming an increasingly important production tool for vegetable, small fruit, and cut flower growers in many parts of the United States. They provide a protected environment relative to the open field, allowing for earlier or later production of many crops, and they typically improve yield and quality as well as disease and pest management. Producers, ranging from small-scale market gardens to larger scale farms, are using high tunnels of various forms to produce for early markets, schedule production through extended seasons, grow specialty crops that require some environmental modification, and capture premium prices. The rapid ongoing adoption of high tunnels has resulted in numerous grower innovations and increased university research and extension programming to serve grower needs. An informal survey of extension specialists was conducted in 2007 to estimate numbers (area) of high tunnels and crops being grown in them by state, and to identify current research and extension efforts. Results of this survey provide an indication of the increasing importance of these structures for horticultural crop production across the country.

Producers of horticultural crops in the United States, and the research and extension specialists who assist them, are increasingly recognizing high tunnels as valuable tools to assist with season extension and crop protection. High tunnels are also sometimes called hoop houses or unheated greenhouses and they include a range of designs from single-span to multi-span structures that are usually covered with a single layer of 6-mil polyethylene greenhouse film. High tunnels may be constructed to be semipermanent, movable, or temporary, although they are usually considered temporary structures for purposes of property assessment and taxation (Blomgren and Frisch, 2007). Typically, high tunnels are unheated and are passively ventilated, but they must have water for

irrigation, and are used to produce a wide variety of crops directly in the soil, or less frequently, in artificial media (Lamont et al., 2003; Heidenreich et al., 2008). In regions with winter snow and ice, the polyethylene film is generally removed from multi-span high tunnels during the winter months, while it is usually left on single-span tunnels, which are often used for the production of winter crops (Blomgren and Frisch, 2007).

Despite having been invented in the United States (Emmert, 1955), high tunnels have not been adopted as quickly by fruit, vegetable, and flower growers here as in many other countries (Wittwer, 1993). While high tunnels or overwintering structures have been widely used in the nursery industry, it was not until the early 1990s that research and extension professionals in the Northeast began to report the high potential of these structures for vegetable production (Wells and Loy, 1993), initially reporting their great advantage for

early production of warm season crops such as tomato (*Solanum lycopersicum*). Multiple efforts, many by innovative growers (Blomgren and Frisch, 2007; Byczynski, 2003; Coleman, 1998, 1999; Wiediger and Wiediger, 2003), have contributed to today's increasing awareness of the potential value of high tunnels for early or extended season production of fruit, vegetable, and flowers of outstanding quality. Because of their low construction and operating costs, it is common for producers to recover their investment within 1 or 2 years (Blomgren and Frisch, 2007).

Today, the use of high tunnels is increasing rapidly in many places in the United States. There are many examples of research and extension programming and education resources being developed around the United States. (Jett, 2004; Jimenez et al., 2005; Lamont et al., 2002, 2005; Nennich et al., 2004). Information on the Internet about high tunnels and their uses has burgeoned over the past decade. Several universities, agencies, and businesses have published digital information about high tunnel construction and use. One university-sponsored website (Kansas State University, 2003) contains original content geared for grower and educator audiences, as well as links to other websites of interest. This website also provides access to an e-mail listserv that is widely used by growers, allied industry, and academics to ask questions and exchange information related to high tunnel use (Kansas State University, 2004).

To attempt to capture a snapshot of current high tunnel use nationwide, we conducted an informal survey of state extension specialists at land grant universities. We present the results of the survey in this article to highlight the growing body of high tunnel research, extension education, and usage by growers in the United States.

Materials and methods

From a list of horticulture extension educators at land grant universities

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	Ha	2.4711
0.0929	ft ²	m ²	10.7639
0.0254	mil	Mm	39.3701

Table 1. Estimated area, number and types of high tunnels, and predominant crops cultivated in them, as reported by state in the United States in 2007. Information was obtained through an informal survey of state extension vegetable specialists and other experts in each state.

State ^z	Estimated area (acres) ^y	Estimated high tunnels (no.) ^x	Major crops
Alaska	About 1	Many small	Green bean (<i>Phaseolus vulgaris</i>), tomato (<i>Solanum lycopersicum</i>), cucumber (<i>Cucumis sativus</i>), greens, herbs
Alabama	<1	10	Tomato, okra (<i>Abelmoschus esculentum</i>), pepper (<i>Capsicum annuum</i>), cut flowers
Arizona	500–1000		Ornamentals
California	>4000	Mainly multispan	Raspberry (<i>Rubus</i> spp.), flowers, some vegetables
Colorado	1.1	24	Salad greens, tomato, flowers, herbs
Connecticut		Hundreds	Primarily nursery crops, limited vegetables
Delaware	<1	5–10	Tomato, squash (<i>Cucurbita pepo</i>)
Florida	50–100		Oriental and leafy vegetables, strawberry (<i>Fragaria × ananassa</i>), raspberry
Georgia	About 1		Transplant production of leafy vegetable crops such as lettuce (<i>Lactuca sativa</i>) and crucifers (<i>Brassica</i> spp.), various organic crops
Hawaii	100	Multispan	Tomato and pepper (50 acres), flowers (50 acres)
Illinois	5	100	Tomato, many other crops
Indiana		50	Tomato, salad greens, strawberry, pepper
Iowa		40	Tomato, greens, cole crops, cut flowers, some herbs
Kansas	About 3	50	Tomato, pepper, lettuce, greens, cut flowers
Kentucky	About 1		Tomato, pepper, lettuce
Maine	About 34	700–1000	Tomato, greens, flowers, cucumber, pepper, zucchini (<i>Cucurbita pepo</i>), raspberry
Maryland		40	Tomato, leafy greens, brambles (<i>Rubus</i> spp.)
Michigan	About 20	>5 acres (single span), 20 acres (multispan)	Tomato, pepper, cucumber, fall/winter salad, mixed vegetables, raspberry, strawberry, sweet cherry (<i>Prunus avium</i>), grape (<i>Vitis</i> spp.)
Minnesota	About 9	200	Tomato, cucumber, pepper, eggplant (<i>Solanum melongena</i>), onion (<i>Allium cepa</i>), garlic (<i>Allium sativum</i>), lettuce, herbs
Mississippi	<1	Many small	Pepper, tomato, squash, cut flowers, strawberry
Missouri	About 7.5	100	Tomato, cucumber, onion, potato (<i>Solanum tuberosum</i>), strawberry, cut flowers, fig (<i>Ficus carica</i>)
Nebraska	About 5	100	Tomato, lettuce, salad mix, cucumber, vegetable transplants, cut flowers
New Hampshire	About 8		Primarily tomato, numerous other vegetables, small fruit, cut flowers
New Jersey	4	Many single span, a few multispan	Tomato, pepper, lettuce, raspberry, cut flowers and herbs
New Mexico	60	>320 units on small farms	Tomato, lettuce, spinach, other vegetables (40 acres), flowers (20 acres),
New York	About 17	240	Tomato, greens, pepper, cucumber
North Carolina	Uncertain		Tomato, mixed winter vegetables, early and late summer vegetables, flowers
North Dakota	<1	About 6	
Ohio	5–8		Tomato, pepper, leafy vegetable transplants, small fruit (e.g., strawberry), flowers
Oklahoma	1–2		Tomato, summer squash, cucumber, winter greens
Oregon	About 100		Blackberry (<i>Rubus</i> spp.), blueberry (<i>Vaccinium corymbosum</i>)
Pennsylvania	34	14 acres (single span), 20 acres (multispan)	Tomato, raspberry, lettuce, mixed greens, strawberry, cut flowers, herbs, organic production

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Table 1. (*Continued*) Estimated area, number and types of high tunnels, and predominant crops cultivated in them, as reported by state in the United States in 2007. Information was obtained through an informal survey of state extension vegetable specialists and other experts in each state.

State ^z	Estimated area (acres) ^y	Estimated high tunnels (no.) ^x	Major crops
Rhode Island		10	Tomato, pepper, herbs, squash
South Dakota	<0.1		Vegetable transplants
Utah		50	Tomato, greens [mustard (<i>Brassica juncea</i>), lettuce, etc.], summer squash, cucumber, strawberry, raspberry
Vermont	About 22	500 tunnels (includes small greenhouses)	Tomato, cucumber, lettuce, greens, pepper, eggplant, miscellaneous vegetables, herbs
Virginia	6	Numerous single span; a few multispan	Tomato, greens, strawberry, cut flowers, organic production
Washington	About 14	50 for vegetables; 8–10 acres of berries (75% strawberry, 25% raspberry)	Tomato, pepper, cut flowers/bulbs, eggplant, watermelon, lettuce, strawberry, raspberry, blueberry
West Virginia	About 1	20	Tomato, flowers, cucumber, salad greens
Wisconsin	>2	>30	Tomato, cucumber, salad greens (spring, fall, and winter), cut flowers, organic production
Wyoming		12	Tomato, leafy greens, a few root crops

^zStates responding with no information on area or numbers or crops: Arkansas, Nevada, Tennessee, and Texas.

^y1 acre = 0.4047 ha.

^xSingle span unless indicated. In temperate regions, multispan tunnels are mostly three-season tunnels.

compiled by W.J. Lamont, Jr., when he served as ASHS Extension Division vice-president, we selected the names of vegetable or food crops specialists to be contacted in the 50 states. In many instances, the initial contacts consulted others to gather the information requested in the survey. The questions asked were: 1) What is the estimated number or area equivalent of high tunnels in your state?; 2) What are the principal crops being grown in high tunnels in your state?; 3) What is the focus of research or demonstration work in your state that you are aware of? Responses were received from 46 states and are presented in Tables 1 and 2.

Results and discussion

Table 1 lists estimates of high tunnel areas, numbers, and principal crops grown in them for states from which responses were received. Respondents were not consistent in their definition of high tunnels. Hence, some respondents included commercial flower production, nursery overwintering structures, or small heated greenhouses (e.g., Arizona, Rhode Island, and Vermont), while many reported tunnels used only for vegetable, fruit, and cut flower production by small acreage farmers. We included all responses received in the survey, but it should be understood that rather than presenting results that are strictly comparable from state to state, the responses are reflective of the high degree of variation in the number and use of high tunnels from state to state and of concomitant variation among states in awareness by extension workers of the current status of high tunnel use by growers in their state.

Most respondents reported that the numbers they provided were just their best guesses because there is currently no mechanism to accurately track high tunnel area, numbers, and crops in most states. The U.S. Department of Agriculture (USDA) census of agriculture does not distinguish between high tunnels and heated greenhouse structures (USDA, 2007). In our survey, some estimates of high tunnel area (e.g., Florida) seem high, but most estimates provided are probably conservative. We did not ask about the average size of operation, but the respondent from Illinois estimated this to be between one and

Table 2. High tunnel fruit, vegetable, and flower research, and demonstration activities reported by extension specialists and others by state in the United States in 2007. Selected references to previously published work are included by state.

State	Principal research/ demo locations	Current research and demonstration topics, and reported results (selected references) ^z
Alaska	Palmer, Fairbanks	Initial stages of research; will crops even survive the winter (Karlsson et al., 2007; Rader and Karlsson, 2006)?
Alabama	Auburn	Fall and spring tomato (<i>Solanum lycopersicum</i>), colored bell pepper (<i>Capsicum annuum</i>), strawberry (<i>Fragaria xananassa</i>), and cut snapdragon (<i>Antirrhinum majus</i>) evaluated with excellent results.
Arkansas	Fayetteville	Organic bramble (<i>Rubus</i> spp.) production research with USDA Integrated Organic Program support.
Colorado	Fort Collins, elsewhere	6000 ft ² in tunnels dedicated to research of diverse vegetable and flower crops under different covering materials focusing on insect-vectored disease mitigation (Organic Farming Research Foundation grant). Planning blueberry (<i>Vaccinium corymbosum</i>) and strawberry work. Many growers are recipients of Colorado State University Specialty Crops Program grower and education grants; their work included feasibility studies, marketing studies, and climate studies. A new project supported by Sustainable Agriculture Research and Education (SARE) program is integrating hog housing and vegetable production.
Delaware		Raspberry (<i>Rubus</i> spp.) demonstration.
Florida		Weather protection, and improved fruit quality, especially with strawberry.
Georgia	Athens	Testing the use of “quasi” tunnels as shelters to produce tomato and pepper during the summer/fall.
Hawaii	Manoa	Research on simple, low-tech hydroponic systems for vegetable production with particular emphasis on tomato, watercress (<i>Nasturtium officinale</i>), ginger (<i>Zingiber officinale</i>), and potato (<i>Solanum tuberosum</i>); trying to find an inexpensive tank system and use a minimum of growing medium.
Illinois	St. Charles, Urbana	Studies of local acclimation, crop suitability, market opportunities, and sustainable optimization. We see high tunnels as a key tool for developing more sustainable production of fruit and vegetables and are looking to expand our work in that area.
Indiana		Proposing larger-scale high tunnels in conjunction with biofuel production.
Iowa	Ames, Harlan	Cropping sequence for tomatoes, tracking production costs, and demonstration of high tunnel technology.
Kansas	Olathe, Wichita	Research and demonstration in half-acre Haygrove ^y three-season tunnel and in four-season single-span tunnels. Inside/outside comparisons, organic/conventional fertility management, and small fruit and vegetable research and demonstration (Kadir et al., 2006; Knewton and Carey, 2007; Spaw and Williams, 2004; Zhao et al., 2007).
Kentucky	Lexington	Demonstration in half-acre multibay and smaller single-span high tunnels (Bomford et al., 2007).
Maine	Orono	Variety evaluations, passive solar heating systems, soil health, cover cropping, and demonstrations.
Maryland	Eastern Shore	Organic salad green production and pest [aphid (<i>Aphididae</i>), mite (<i>Acari</i>), and thrips (<i>Thysanoptera</i>)] control.
Michigan	Lansing, Benton Harbor, Clarksville	Research on strawberry, raspberry, blueberry, sweet cherry (<i>Prunus avium</i>), pepper, and tomato in multibay tunnels. For three-season and four-season tunnels, focus is on season extension, quality improvement, variety screening, enterprise budgeting, market research, farmer interviews to measure the viability of high tunnel technology, year-round production, training future farmers, organic production, direct marketing, risk management, training the trainer model for construction and usage, modeling crop production and timing schedules, economic analysis, benefits of season extension to farmer's markets and on-farm stores, online course development, agritourism, energy studies in comparison with imported produce (from outside Michigan), community development, effects of season extension on human health and well-being especially in terms of the elderly and rural communities, and the creation of model business plans for high tunnel users based on various marketing decisions (Lang, 2009; Montri and Biernbaum, 2009).
Minnesota	Grand Rapids, Staples, Crookston (organic), Waseca	Variety trials, tomato pruning, spacing, fertility, slow-release fertilizer, intercropping, and irrigation. Numerous SARE producer grants are funded in the state (Nennich et al., 2004).

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Table 2. (Continued) High tunnel fruit, vegetable, and flower research, and demonstration activities reported by extension specialists and others by state in the United States in 2007. Selected references to previously published work are included by state.

State	Principal research/ demo locations	Current research and demonstration topics, and reported results (selected references) ^z
Mississippi	Beaumont, Mississippi State	Vegetable and cut flower research.
Missouri	Columbia	No current activity. Previous vegetable and small fruit research in single-bay high tunnels (Jett, 2004, 2006).
Nebraska	Lincoln	Cut flowers, economics, microclimate modification, and biological control of insects and diseases.
New Hampshire	Durham	Cut flower (<i>Eustoma</i>) production, early colored bell pepper variety trials, overwintering crucifers (<i>Brassica</i> spp.) for spring harvest, and tomato disease [leaf mold (<i>Fulvia fulvum</i>)] biocontrol (Wells, 1996; Wells and Loy, 1993).
New Jersey	Centerton, Brunswick	Research on engineering aspects of high tunnels and tomato production (Both et al., 2007; Reiss et al., 2004).
New Mexico	Northern New Mexico	Workshops on tunnel construction and use for smaller scale vegetable and ornamental production (Jimenez et al., 2005).
New York	Ithaca	Biological pest management, crop rotation, impacts of different plastics on microclimate, cut flower and small fruit research, and on-farm applied research on cultural practices, varieties, and pest management (Blomgren and Frisch, 2007; Heidenreich et al., 2008; Wien, 2009).
North Carolina	Greensboro	Grafting tomato, small fruit (strawberry), and winter production of greens.
Ohio	Wooster	Season extension and testing soil fertility, organic transition, polyculture, and disease and insect management strategies or tools in conventional, sustainable, and organic systems and grafting.
Oklahoma	Lane, Ardmore (Noble Foundation)	Early carrot (<i>Daucus carota</i>) and onion (<i>Allium cepa</i>) transplant production, cherry/grape tomato variety trials and economics of high tunnel crop rotations: spinach (<i>Spinacea oleracea</i>)–tomato–squash (<i>Cucurbita pepo</i>) and annual strawberry–squash.
Pennsylvania	Rock Springs, elsewhere	Specialty crops [ginger, watercress, and taro (<i>Colocasia esculenta</i>)], all vegetables (conventional and organic), strawberry, raspberry, blackberry, herbs, cut flowers, and hydroponic lettuce (<i>Lactuca sativa</i>). Applied research/demonstrations at 14 cooperative (growers or teachers/extension) high tunnels located throughout the state (Lamont, 1996; Lamont et al., 2002, 2003, 2005; Orzolek et al., 2004).
Tennessee	Knoxville	Plans for high tunnel research at new university organic farm.
Utah	Provo	Production information (organic and conventional) for winter (greens for late fall–early spring) and summer (tomato, squash, and pepper) crops, including production budgets. Raspberry in soil (permanent plantings) as well as in pots (pot-in-pot and aboveground pots) for season extension (early and late). Strawberry for spring annual production (in-ground and in-gutters). Growers cooperating around Utah as part of SARE grant for 2007 to 2010.
Vermont		Grafting greenhouse tomato, renewable energy (heating) systems, and organic production methods.
Virginia	Petersburg, Blackstone	Season extension for small farmers who are direct marketing. Demonstration and research on crops include cut flowers, organic vegetables, raspberry, strawberry, tomato, various others. Work is conducted in 6000 ft ² of quonset tunnels and 21,000 ft ² Haygrove ^y . On-farm demonstrations on construction, season extension, and specialty crops. Virginia Tech Southern Piedmont Agricultural Research and Extension Center has a Haygrove ^y around 21,000 ft ² , mainly for strawberry research.
Washington	Mount Vernon	Lettuce and Asian greens for winter production, watermelon (<i>Citrullus lanatus</i>)/tomato rain shelter effects, and strawberry, raspberry, and blueberry research (Miles and Labine, 1997).
West Virginia	Morgantown	Plan to build four high tunnels in 2007 for vegetable and strawberry research.
Wisconsin	Green Bay	High tunnel microclimate and crop response, berry production that focuses on labor issues, and extension demonstration (Wright, 2005).
Wyoming	Laramie, Sheridan	Strawberry, green pepper, cool season vegetables, tomato.

^z1 ft² = 0.0929 m²; 1 acre = 0.4047 ha.

^yMulti-bay, three-season tunnel (Haygrove Ltd., Ledbury, UK).

four 2000-ft², single-bay tunnels. The average size of operation for multi-bay operations would be larger (several states reported these) because these typically have a minimum size of 0.5 acre. Mechanisms for more accurately tracking high tunnel acreage, crops, and grower needs would be desirable.

While many crops were reported to be grown in high tunnels (Table 1), the widespread importance of some crops was noteworthy. For most states, tomato was among the first crops reported. High-tunnel tomato crops are typically ready to market earlier than the field-grown crop, and they typically produce a higher quality crop with fewer requirements for inputs (Blomgren and Frisch, 2007; Jett, 2004; Nennich et al., 2004). The extent to which high tunnels are used for fall and winter production of cool season leafy green vegetables is not entirely clear from Table 1, but this is likely an important component of production in many states of the continental United States, ranging from Michigan to New Mexico. The widespread reporting of cut flowers is noteworthy, as are reports of small fruit production from many states, affirming that these crops can be profitable in high tunnels (Heidenreich et al., 2008; Wien, 2009). High tunnels are amenable to large-scale production, with raspberry (*Rubus* spp.) production in California being the most striking example, but in most states, high tunnels are being used by relatively small-scale producers to serve local markets (Table 1).

Table 2 summarizes high tunnel vegetable, fruit, and flower research and extension activities reported by state. Again, the list is certainly not complete, but it indicates that horticultural researchers and extension personnel in many states reported conducting activities aimed at assessing the potential of high tunnels, of researching particular production systems or problems, or demonstrating the benefits of high tunnels. The large number of states with active or incipient programs, and the large number of crops and management topics being addressed are indicative of significant needs and opportunities for high tunnel research and extension around the country, and of funding opportunities to help support these efforts. Because high tunnels are unheated and passively cooled, crop

selection and management will be determined by local environmental conditions. This, and the previous lack of research on high-tunnel production systems in the United States, provide a strong justification for broadly decentralized research and extension efforts.

Conclusions

From the results of the survey and literature cited, it is evident that producer interest in and adoption of high tunnels is high, and there is a wide variety of research and extension activities ongoing around the country. In most places, high tunnel fruit, vegetable, and flower production, and research and extension efforts are primarily geared toward responding to growing demand for fresh, locally grown produce. With the considerable environmental protection that high tunnels provide to crops, and with growing producer awareness of the advantages these structures provide, continued expansion of acreage and diversification of crops grown in high tunnels is likely in the United States. We can look forward to an expanding body of research and practical knowledge to meet the needs of producers.

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