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VARIETY TRIALS AND PRODUCTION METHODS FOR
VEGETABLE AMARANTH IN THE NORTHEAST

BY

SARAH SCHWEIG

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

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MASTER OF SCIENCE THESIS
OF
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ABSTRACT

This study investigated the production of amaranth (*Amaranthus* spp.) as a leafy green in the northeastern temperate climate. Amaranth is a productive and resilient crop with cultural, economic, and nutritional significance to many cultures around the world. Growing ethnic crops in the northeastern U.S. is an opportunity for growers to expand into new and diverse markets. Amaranth's pervasiveness in global foodways and tolerance of many biotic and abiotic stresses make it a promising option for growers to engage with the ethnic produce market and diversify production. However, intensive production research for vegetable amaranth is lacking, especially in temperate climates, and amaranth varieties are underdeveloped.

In 2016, ten vegetable amaranth varieties were evaluated for performance in the northeastern temperate climate. The experiment was a randomized complete block design with four replications and ten plants of each variety per replication. Yields of each plot and leaf to stem ratios of a two-plant subsample per plot were recorded. CVs were calculated for each variety as a measure of yield stability. The varieties included eight commercially-available *A. tricolor* varieties ('Asia Red,' 'Red Garnet,' 'Red Callaloo,' 'Green Pointed Leaf,' 'Red Stripe Leaf,' 'Miriah,' 'Southern Red'), one commercially-available *A. viridis* variety ('Green Callaloo'), and one heirloom *A. hybridus* variety from Burundi ('Mchicha'). All plants were greenhouse-started and transplanted to a low-tunnel system, constructed with galvanized metal hoops and 0.8-mil clear slitted plastic. The experiment was repeated seven times over the 2016 growing season. There was little variation between the varieties in the middle of the summer. However, two varieties that excelled in the early and late season ('Green Pointed Leaf'

and ‘Miriah’) were also top performers all-season. Targeted production and marketing strategies have the potential to improve variety desirability.

A comparison of plasticulture production systems for vegetable amaranth was also conducted during the 2016 growing season. Two varieties of *A. tricolor* (‘Red Stripe Leaf’ and ‘Green Pointed Leaf’) were used throughout the experiment. The four treatments were 1) gothic-style high tunnel covered in a double inflated layer of 6-mil greenhouse plastic; 2) low tunnels over raised beds with black plastic mulch, constructed with galvanized hoops covered in 0.8-mil clear slitted plastic; 3) raised beds with black plastic mulch; and 4) uncovered bare soil. A split-plot design with 10 plants in each plot and four replicates was repeated three times over the season. High tunnel plots were excluded from the second planting due to extensive Woodchuck (*Marmota monax*) damage. Low tunnel plots had the greatest yields in every planting. The magnitude of production system effects decreased as ambient temperatures increased throughout the season. However, rankings of the four production systems were consistent in each experiment. Yield rankings from greatest to least were: low tunnel, black plastic mulch, high tunnel (when present), and bare soil. There were occasional significant differences in leaf to stem ratios. However, the response did not follow a discernable pattern based on production system, nor was it correlated to yield. Leaf to stem ratio is likely genetic and outside the influence of production system.

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PREFACE

This thesis is written in manuscript format. Two chapters are formatted for submission to the journal HortTechnology.

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CHAPTER 1

INTRODUCTION

Diversified cropping systems are important in reducing economic risk and environmental impact for small and beginning farms. By incorporating alternative crops, these growers may also benefit from expansion into new markets (Fritz and Meyers, 2004). One such market, which is receiving increased attention, is the ethnic crop market. As the United States population becomes more diverse, the foods and flavors that are valued by cultures around the world are becoming increasingly popular (Ballenger and Blaylock, 2003). In 2015, recent immigrants and their U.S.-born family members comprised 27% of the U.S. population, and this percentage is projected to continue to rise (U.S. Census Bureau, 2015). These shifting demographics represent an expanding market of consumers seeking their traditional produce. Additionally, diverse communities lead to an expansion of the American “food repertoire,” which broadens the customer base for traditional ethnic foods (Ballenger and Blaylock, 2003).

Amaranth (*Amaranthus* spp.) is an attractive option for growers interested in connecting to the ethnic crop market because of its particularly wide cultural significance. Amaranth is a common green in many Asian, Latino, African, and Caribbean cultures, and competition from imports is extremely minimal. Amaranth leaves are also highly nutritious and often striking in color, qualities that lend favorably to marketing as a novel substitute for more common greens (National

Research Council, 2006). However, by nature, the marketing chains and production protocols for alternative crops are not well defined. Although *Amaranthus* species inhabit a wide range of latitudes, cultivar-level research is sparse on suitability for intensive production in temperate climates. Studies suggest that variety sensitivities to temperature, moisture, and photoperiod are varied (Campbell and Abbott, 1982; Wu et al., 2002). Furthermore, the shortage of regional production research means little is known about ancillary issues such as transplant tolerance and pest and disease occurrence. Amaranth varieties are less developed than more common vegetables, making replicated, regionally-focused research especially important in determining the performance and stability of available varieties.

Amaranth is a heat-loving C4 crop, and its culture will differ significantly from popular spring and fall greens (Teutonico and Knorr, 1985). Plasticulture systems, including plastic mulches, drip irrigation, and plastic crop covers, are often used to enhance the yields of warm-weather crops in temperate climates. The increased rate of heat accumulation in these systems is closely linked to increased vegetative growth in heat-loving crops; varying degrees of season extension are also possible. A wide spectrum of plasticulture designs and techniques are available to growers, and the fitness of a particular design is largely dependent on target crops, target markets, and existing production strategies (Wells and Loy, 1993). Small and beginning farmers who are interested in implementing plasticulture strategies require research-based information on the trade-offs associated with various plasticulture system-crop combinations. Given amaranth's affinity for high heat, it is likely that plasticulture production would be of some benefit in the northeastern region. Direct investigation of

plasticulture amaranth production is warranted due to significant differentials in temperature requirements and light saturation points, relative to more common crops. Studies have reported successful amaranth production with black plastic mulch and drip irrigation, but the use of crop covers has not been investigated (Meyers et al., 2010; Sciarappa, 2016).

The primary objectives of this study were the following:

1. Evaluate vegetable amaranth varieties for plasticulture production in the northeastern temperate climate.
2. Assess the benefit of three plasticulture systems for vegetable amaranth production in the northeastern temperate climate.

CHAPTER 2

REVIEW OF LITERATURE

AMARANTH

Amaranth refers to plants of the genus *Amaranthus*, which contains 60-70 species of annual, mostly monoecious, plants with an upright, moderately branched growth habit. Amaranths are cultivated for ornamental, grain, or vegetable production, but most species are classified as weeds, including the well-known and troublesome pigweeds (Teutonico and Knorr, 1985). Separation of these types is not entirely distinct, taxonomically or functionally, because all *Amaranthus* species have edible stems, leaves, and seeds. The young leaves of grain types are commonly eaten as greens, and, although the domestication of wild amaranths began over 2,000 years ago, many more species are eaten globally than would be considered truly domesticated. Amaranths have not been the subject of modern intensive breeding efforts, and frequent hybridization between cultivated and wild populations has led to the existence of many intermediate types (National Research Council, 2006). Amaranths have a high capacity for osmotic adjustment (Liu and Stutzel, 2002) and a C4 photosynthetic pathway that allows efficient use of CO₂ in a large range of temperature and moisture stress environments, likely a major factor in their wide geographic distribution (Stallknecht and Schulz-Schaeffer, 1993).

Amaranth is grown and eaten as a vegetable in over 50 countries worldwide, in such geographically diverse locations as South America, Nepal, China, Greece, India, and South Pacific Islands (National Research Council, 2006). Nutritional assessments of common vegetable species (*A. blitum*, *A. cruentus*, *A. dubius*, *A. tricolor*, and *A. viridis*) show high protein content and significant levels of essential micronutrients, including beta-carotene, iron, calcium, vitamin C, vitamin A, and folic acid (Achigan-Dako et al., 2014; Mziray et al., 2001; Teutonico and Knorr, 1985). High nutritional value and tolerance of many biotic and abiotic stresses have made amaranth an especially important vegetable crop in Africa, where some societies derive as much as 25% of their protein intake from amaranth leaves during the production season, and its sale by the thousands of tons annually has significant economic impact (Mandu et al., 2012; National Research Council, 2006). Nonetheless, amaranth has historically been considered a resource of the lower classes, and the phrase “not worth an amaranth” exists in multiple African languages. In contrast, in the Caribbean, amaranth has acquired symbolic cultural significance, in addition to being a dietary staple. The Creole word *callaloo*, which refers to both amaranth plants and a traditional stew made with amaranth, is also used with great pride colloquially to indicate the unique blend that constitutes Creole culture (National Research Council, 2006). Though cultural views of amaranth vary by location and socioeconomic class, its pervasiveness and significance globally are without dispute. The primary *Amaranthus* species eaten as a vegetable include *A. tricolor*, *A. cruentus*, *A. dubius*, *A. caudatus*, *A. hybridus*, and *A. viridis*. Amaranth leaves and stems are steamed, used in soups, boiled in several changes of water, or young leaves are eaten raw (Achigan-Dako et al.,

2014). While amaranth seed production in the U.S. is around 6,000 acres, centered in the Great Plains region, commercial vegetable amaranth production is effectively non-existent and requires increased research (Green, 2003).

ETHNIC CROP OPPORTUNITIES

Advocates for increased vegetable amaranth production and research in the U.S. cite amaranth's wide use by cultures around the world as the primary appeal for farmers (Singh and Whitehead, 1996; Whitehead and Singh, 2002). Immigrants made up over 13% of the U.S. population in 2014, and this percentage is expected to reach an all-time high in 2025, surpassing the current record set in the 1890s (U.S. Census Bureau, 2016). The USDA Economic Research Service has identified increased diversity of the U.S. population as one of the three most important influences on future U.S. food markets (Ballenger and Blaylock, 2003). Recognition of this fact has been the impetus for extensive ethnic crop marketing studies in the ethnically diverse northeast region, focusing on Asian, African, and Latino populations (Govindasamy et al., 2006; Govindasamy et al., 2007; Mangan et al., 2008; Sciarappa et al., 2016). It is important to note that these studies grouped respondents into ethnic groups, rather than by immigration status. Even so, Govindasamy et al. (2006) found that 80% of survey respondents regularly purchased ethnic produce and that this sub-group spent 40-80% more on produce than those who did not regularly purchase ethnic produce, making the case for ethnic crop production even stronger than immigration numbers would suggest. Vegetable amaranth was identified as one of many relevant ethnic crops in

these surveys, and ranked in the ten most frequently purchased vegetables for Indian survey respondents (Govindasamy et al., 2006; Govindasamy et al., 2007; Sciarappa et al., 2016).

These surveys also found that ethnic produce purchasers frequently bought produce at multiple types of markets, expressed a willingness to pay a premium for their native produce, and cited freshness and availability as the main reasons for market selection. When asked specifically if they desired to buy more ethnic produce grown locally, two-thirds of respondents answered affirmatively and only 6% answered negatively, with the remaining respondents indicating they were unsure (Govindasamy et al., 2006).

These key regional studies indicate that ethnic crops can offer local growers an opportunity to expand into an eager market of consumers seeking their traditional produce. Amaranth is a particularly strong candidate for local production and direct to consumer sale because sensitivities to temperature and low relative humidity make long-distance shipping challenging (Wheeler et al., 2015). Rhode Island had 38 regularly scheduled farmers' markets in 2016 (Rhode Island DEM, 2016). In these direct sales systems, ethnic crops may also appeal to high-end buyers who value produce options outside of their everyday fare.

In continued ethnic crop research at the University of Massachusetts Amherst, Mangan et al. (2008) have found that a vast majority of tropical ethnic vegetables are easily produced in New England and that the advantages of proximity to a diverse and densely populated market outweigh production challenges. Successful entry into the ethnic crop market, however, requires that farmers be armed with region-specific

production information and an understanding of the markets for unfamiliar crops (Govindasamy et al., 2006; Govindasamy et al., 2007; Mangan et al., 2008).

PRODUCTION

In comparison to the deep pool of cultural knowledge surrounding amaranth, intensive production research is lacking. Amaranths are known to tolerate marginal soils, high heat, and drought, and have been reported to display a general resilience and resistance to common pests and diseases. Studies investigating these assumptions as they relate to production protocols, however, have returned varying results. Existing literature is comprised of experiments with a large geographic and climatic range, often studying different species with little replication, so this variation is expected. Amaranth varieties generally have not been as developed as many more common vegetables and therefore vary in their uniformity and adaptation to temperate climates (Putnam et al., 1989). Wu et al. (2002), in one of the most extensive field evaluations of *Amaranthus* spp. in both temperate and tropical regions of China, found plant performance varied significantly between the two climates and found a great deal of agronomic trait variation between species and between genotypes within species. Photoperiod sensitivity and origins of genotypes were more strongly correlated to performance in different climates than was plant species. Consequently, in evaluating what information can be gleaned from existing production research, the location of and cultivars used in the studies should be given careful consideration.

Fertility

While amaranths are known to perform well in poor soils, they also respond positively to nitrogen (N) fertilization. Singh and Whitehead (1996) found that for a Taiwanese genotype of *A. tricolor*, all yield parameters studied increased linearly with N fertilization up to 80 lb/A of N. Onyango et al. (2012), studying *A. hypochondriacus* in Nairobi, Kenya, reported an increase in yield with up to 53 lb/A of N but reported three other important observations: First, the effect of fertilization on growth was largely saturated at only 18 lb/A of N. Second, 35 lb/A of chemical N was optimum in balancing high yield with low nitrate accumulation. And lastly, there was a significant interaction of harvest time with the effect of fertilization on growth and nitrate accumulation (*i.e.* the effect of increased fertilization on growth increased with later harvest time, and the effect of increased fertilization on leaf nitrate levels decreased with later harvest time). Published production guidelines and amount of N reported for optimum growth by researchers range from 45-178 lb/A of N, and it has been suggested that previous planting in legumes may provide sufficient N for commercial amaranth production (O'Brien and Price, 1983). All studies agree that amaranth fertility needs will be most dependent on pre-existing soil composition.

Common African amaranths (*A. caudatus* and *A. cruentus*) have been shown to respond well to organic sources of N (AdeOluwa et al., 2009; Edomwonyi and Opeyemi, 2009; Makinde, 2015). Organic fertilization strategies also limit nitrate accumulation (Onyango et al., 2012). With the positive relationship between N fertilization and amaranth yield well established, future focus should be on taking

advantage of amaranth's low fertility requirements to prevent nitrate accumulation, nutrient leaching, and expenditure for farmers.

Temperature Requirements

While a general affinity for high temperatures pervades *Amaranthus* spp., reports of temperature requirements are mixed. Stallchknecht and Schulz-Schaeffer (1993) reported that amaranth seeds need soil temperatures of 15°C for germination, while Putnam et al. (1989) and Wagoner et al. (1983) describe most amaranth species germinating when soil temperatures reach 18°C. An *A. tricolor* planting date study in Georgia, however, found seeds did not germinate in the field until soil temperatures reached 25°C (Singh and Whitehead, 1996). Optimal day-time air temperatures for growth have been reported as 30-40°C, and night-time temperatures as 22-28°C. This variation in reported temperature requirements is not surprising due to the range of species under consideration and the less refined (and therefore variably performing) nature of amaranth cultivars. However, it is problematic in the pursuit of amaranth production protocols for the northeastern temperate climate. For amaranth production in climates where heat tolerance is at issue, evidence of a generalized affinity for high heat may be sufficient; in the northeast, where cool night-time temperatures are at issue, temperature requirements are acutely relevant.

Pests

Unlike cool-season greens, amaranth grows in times of high disease and pest pressure (Makus, 1984), but no production studies listed prohibitive pest or disease

issues. Amaranth is considered tolerant of nematodes and has been suggested to reduce nematode populations for subsequent crops in rotation cropping (O'Brien and Price, 1983). Production guides list the lygus bug (*Lygus lineolaris*) and European corn borer (*Ostrinia nubilalis*) as principle insect pests, but these insects affect amaranth inflorescences, making them more detrimental to grain production than vegetable (Ebert et al., 2011). The amaranth weevil (*Conotrachelus seniculus*) and foliar insects can also feed on amaranth, but amaranths are known to be generally resilient to herbivore attacks and resistant to bacterial and fungal wilt (Achigan-Dako et al., 2014). Furthermore, common insect pests may show a preference for wild amaranth species when present (Makus, 1984); in fact, pigweed can serve as a companion plant for trapping leaf miners and other pests (Maynard, 2013). Because it is not typically grown here, very little information on amaranth pests and diseases specifically in the northeast is available, but Maynard (2013) reported that no pest or disease intervention was required in a three-year vegetable amaranth study in Connecticut.

Photoperiod Sensitivity

Given amaranth's adaptation to conditions from equatorial to temperate, it is not surprising that reports of photoperiod sensitivity vary. The photoperiodism of grain, ornamental, and weedy amaranths have received more attention than that of vegetable amaranths, and a wide range of responses have been reported. Most common weedy amaranths exhibit facultative short-day flowering, but it has been suggested that northern populations are more sensitive to decreasing day-length than

southern populations of the same species (Holm et al., 1997). *A. caudatus*, which has been cultivated for grain production but is also eaten as a vegetable, exhibits facultative short-day flowering (Atherton, 1987; Kulakow and Jain, 1985). Grain amaranth variety trials in Minnesota, however, reported a range of day-length flowering requirements, from short to long (Robinson, 1986).

‘Pygmy Torch’ amaranth, which is often listed as *A. hypochondriacus* or *A. hybridus* is a popular day-neutral ornamental amaranth (Erwin et al., 2002). As a note of clarity, *A. hybridus* is the progenitor species of a group of *Amaranthus* species that are best-known as grain types but are also widely eaten as greens. Species within this group are genetically distinguishable from one another and from *A. hybridus*. However, *A. hybridus* may refer to interspecific hybrids within this “*A. hybridus* complex,” or be used cautiously in the absence of genetically precise identification (Drzewiecki, 2001). Given the characteristic genetic diversity of *A. hybridus*, it is not expected that the day-neutral photoperiodism of ‘Pygmy Torch’ would apply to the entire species or the *A. hybridus* complex. Extensive *Amaranthus* spp. field evaluations by Wu et al. (2002) indicate genotypic differences in photoperiodism within some species, including *A. hybridus*. Plants of 229 genotypes of 20 *Amaranthus* species from 36 countries were grown in both tropical and temperate plots; the temperate plot was located in Beijing, at a latitude similar to Rhode Island. Although photoperiod sensitivity was not studied directly, Wu et al. (2002) attributed much of the developmental differences observed in the two climates to photoperiod sensitivities. All genotypes of 12 species completed full growth cycles in both temperate and tropical climates. This potentially day-neutral group included two

common vegetable species, *A. viridis* and *A. dubius*. Response within other common vegetable species was less homogenous. For example, 20 out of 29 *A. hybridus* genotypes and three out of 19 *A. tricolor* genotypes only produced seeds in tropical plots (Wu et al., 2002). Achigan-Dako et al. (2014) report that vegetable amaranths typically exhibit facultative short-day flowering, but the level of sensitivity varies with species and cultural practices.

It does not seem reasonable to extrapolate results of photoperiod sensitivity studies across species, nor to draw specific conclusions from the observations of Wu et al. (2002). However, the wide range of observations from these studies is noteworthy, as is the lack of evidence of any obligate photoperiod-sensitive flowering. Wu et al. (2002) suggest that matching variety origin to target production area may be useful in accommodating photoperiod sensitivities, which appear to be significant in some cases, if not entirely understood.

Cultivar Selection

Amaranth's affinity for high heat makes it an appealing crop for commercial production because it can thrive in the warmest summer months when production of comparable leafy vegetables can be challenging (Makus, 1984; Singh and Whitehead, 1993). In the southern U.S., where this is of particular interest, sensory and field evaluations of vegetable amaranths have been conducted. Taste test respondents rated *A. tricolor* comparable to spinach (Abbott and Campbell, 1982; Makus, 1984) and more appealing than *A. cruentus* and *A. dubius* (Abbott and Campbell, 1982). An evaluation of *A. tricolor* in Arkansas found six of the eight East Asian accessions

yielded significantly less than the semi-savoy spinach grown for comparison. There were no significant yield differences among the *A. tricolor* accessions, and sensory ratings were largely favorable. Sensory scores were a composite of appearance, smell, texture, bitterness, taste, and after-taste scores of freshly cooked amaranth leaves (Makus, 1984). Five cultivars representing *A. tricolor*, *A. dubius*, and *A. hybridus* were compared for productivity, nutritional qualities, and resistance to damping-off in central Texas; 'Ibondwe,' a cultivar of *A. dubius* sourced from West Africa, excelled in all categories (Sealy et al., 1990).

These southern U.S. cultivar selection studies are not exhaustive, however, and they do not lend themselves to comparison with one another due to inconsistent cultivar selection. Furthermore, potential sensitivities to photoperiod and temperature differentials decrease their reliability in the northeastern region. This caution is confirmed by vegetable amaranth field evaluations in Maryland and Pennsylvania. This study included 20 accessions, representing *A. tricolor*, *A. dubius*, and *A. cruentus*. The only *A. dubius* accession evaluated had the highest yield in optimum environmental conditions, but was also the most affected by cooler and wetter conditions (Campbell and Abbott, 1982). Amaranth cultivar selection in the northeast should proceed with the acknowledgement that much of the viable growing season could include sub-optimum conditions for amaranth.

Recent vegetable amaranth variety trials, conducted at the Connecticut Agricultural Experiment Station from 2008-2010 by Maynard (2013), will lend most easily to comparison with this project and future studies in the region. Maynard (2013) evaluated eight commercially-available *A. tricolor* cultivars at two different locations.

Some consistent patterns, but few significant yield differences, were observed over the three-year study. ‘All Red’ produced the greatest yields overall, but ‘Red Stripe Leaf’ produced the greatest yields in 2009. These two varieties were statistically equal in all locations and plantings, and often statistically equal to all but the lowest-yielding varieties. ‘Bayam’ and ‘White Leaf’ were consistently low-yielding varieties. However, these varieties only yielded significantly less than the top one or two varieties in any planting (Maynard, 2013).

The climates of Connecticut and Rhode Island are similar enough that we can expect comparable variety performance in these two locations. The common cultural practices associated with growing heat-loving crops in temperate climates are also noteworthy for the comparison of these studies. Amaranth seeds are very small and prone to crushing, so they are often directly broadcast-seeded in warmer climates (Ebert et al., 2011). However, in more temperate climates, starting seeds in a greenhouse or other protected structure is one of the primary ways of extending the season of heat-loving crops and maximizing production. Maynard’s (2013) variety trials in Connecticut used greenhouse-started transplants, whereas Campbell and Abbott (1982) direct seeded in Maryland and Pennsylvania. Transplant response of amaranth has not been directly studied, but it has been suggested in growers’ guides that some varieties of *A. tricolor* do not respond well to transplanting (Ebert et al., 2011). In the absence of detailed transplanting tolerance information, variety recommendations that account for response to transplanting may be most useful to growers in the northeast.

Maynard (2013) harvested varieties repeatedly, which is a common practice with amaranth and may delay flowering. However, it is possible that reporting cumulative yields of the repeated harvests masked some of the differences in variety performance. Furthermore, the varieties evaluated by Maynard (2013) encompassed a range of appearances and sizes. Heights ranged from 1.5 feet for dwarf varieties, to 3 feet; leaf colors included light green, purple, and red and green variegated. Especially for growers who are unfamiliar with amaranth, yield comparisons over an entire season may paint an oversimplified picture of variety desirability. Growers might find yield stability measures and descriptive measures, such as leaf to stem ratio, useful supplemental information.

PLASTICULTURE

The benefits of plasticulture vegetable production systems are season extension, efficient use of resources, and increased crop yield and quality. In the northeastern region, these systems are commonly used to increase the growth rate of heat-loving crops and extend the season for high value crops (Lamont, 1996; Wittwer, 1993). The basic structural components of plasticulture, including plastic mulches, plastic films and coverings, and drip irrigation, are employed to modify the microclimate surrounding the plants. These structural components can be used by small- or large-scale growers, but the ideal combination of materials, structures, and management techniques depends upon the grower's budget and scale, as well as the target production area, crops, and market (Waterer, 2003).

Tanner (1974) outlines in detail how the interaction of components in a plasticulture system produces an effect greater than the sum of its parts. Plastic mulches affect the microclimate mainly by modifying the ratio of absorbitivity to reflectivity of the surface (Tanner, 1974). Black plastic mulch, the most widely used color in vegetable production, generally increases soil temperatures at a 5cm depth by 2.8°C during the day, compared to bare soil (Lamont, 1996). Energy absorbed by black plastic mulch that is not transferred to the soil will be reradiated as thermal radiation; protective structures like high tunnels and row covers can be used to reduce this energy loss. While protective structures do produce a greenhouse effect, their greatest contribution to microclimate modification is in wind protection, preventing energy gains from “mixing away” into the surrounding atmosphere and thereby amplifying the effect of plastic mulch (Tanner, 1974).

Similarly, drip irrigation alone reduces water needs, relative to surface irrigation, but has the greatest effect when combined with plastic mulch. Plastic mulch both reduces evaporative water loss and prevents competition for water by controlling weed growth. The irrigated soil, in turn, provides a more conductive surface for the transfer of energy from plastic mulch to soil (Tanner, 1974). Plastic mulches also reduce fertilizer leaching (especially when fertigated through drip irrigation systems), reducing input costs for growers and environmental impact (Lamont, 1996). While all plasticulture systems utilize these foundational microclimate modification concepts, the benefit of a given design will vary based on materials, structures, climate, and crops. Those potential benefits must be weighed against the capital investment and labor associated with each system.

This review will focus on high tunnels and low tunnels, the two most widely used structures (after greenhouses) for enhancing yields and extending the season in temperate climates. Both of these structures are impermanent, unheated, and present relatively low-cost options for lengthening the growing season and enhancing yields (Wells and Loy, 1993). A comparison of the two systems demonstrates the spectrum of tradeoffs growers must often consider when evaluating plasticulture designs.

Low Tunnels

Low tunnels, or hoop-supported row covers, are typically made of 18-26 μm thick polyethylene sheets supported by metal hoops. The ends and sides of the plastic are secured to the ground using stakes, weights, or by burying in the soil. The first plastic row covers were solid plastic designed to minimize night-time heat loss, which required manual ventilation during the day and closure in the early evening (Wells and Loy, 1993). The development of slitted and perforated row covers alleviated this high labor cost and diminished the risk of destruction by strong winds at night (Wells and Loy, 1985a). Although crop maintenance beyond irrigation still necessitates the removal of covers, slitted or perforated covers may potentially be left in place until time of harvest or until plants outgrow the structures, substantially reducing labor cost (Wells and Loy, 1993). This reduction in labor requires a compromise on night-time temperature control, but covers that can be left in place during the day accumulate more heat units over time and provide crop protection. In fact, whether solid or slitted, row covers of a thickness that will provide adequate light transmission cannot provide significant frost protection (2°C to 3°C maximum); instead, their benefit is mainly in

these accumulated heat units, which result in large part from temperatures in the tunnels rising faster than ambient temperatures in the morning (Wells and Loy, 1985a).

High Tunnels

High tunnels, conceptually, fall somewhere between low tunnels and greenhouses. High tunnels can differ somewhat in their frame shape, but all designs resemble a plastic-covered greenhouse. High tunnels are typically covered with a single or double layer of 4-mil to 6-mil thick plastic (Wells, 1996). High tunnels are passively ventilated, have no active heating system, and do not provide the same level of environmental control as a greenhouse. Consequently, high tunnels are intended for season extension, rather than the year-round production possible in greenhouses. Ventilation is most commonly achieved by rolling up the sides of the tunnel, so tunnel length has no effect on ventilation. However, tunnel width in excess of 20ft may diminish vent effectiveness in high ambient temperatures (Wells and Loy, 1993). In contrast to low tunnels, high tunnels typically span multiple rows of crops and are tall enough for comfortable entry, making crop access and maintenance effortless; crops may grow to full maturity without adjustments. Raised beds may be constructed within high tunnels, or crops can be grown directly in tilled soil, with or without the addition of plastic mulch (Waterer, 2003).

While more heat units are accumulated under low tunnels than high tunnels, that benefit ceases if and when low tunnels must be removed due to crop growth. High tunnels have a greater initial cost than low tunnels, but once constructed, have low

operation cost and are much more durable (Waterer, 2003). When growing high value crops, Blomgren and Fisch (2007) estimate that most high tunnel growers reclaim their high tunnel investment in one to two years; Waterer (2003) estimates a full return in two to five years. However, the relatively recent development of the NRCS Environmental Quality Incentives Program (EQIP) High Tunnel Initiative drastically changes the balance of these equations. EQIP provides financial support and training for the implementation of conservation practices; the EQIP High Tunnel Initiative began in 2010 and is now active in all 50 states (NRCS, 2017).

Considerations for Amaranth Production

Within each of these systems, there is ample room for variation regarding management and selection of materials, and both high and low tunnels have been found to be potentially economically viable season extension options in the northeastern U.S. (Wells and Loy, 1993). Black plastic mulch and drip irrigation have been used successfully for intensive amaranth production studies in Maryland (Meyers et al., 2001) and New Jersey (Sciarappa et al., 2016), but production system comparison was not the focus of these studies; the use of crop covers for amaranth has not yet been studied.

Often, in covered plasticulture systems, a balance must be struck to maximize desired heat accumulation without reaching temperatures that may damage crops (Wells and Loy, 1985a; Wells and Loy, 1993). Amaranth thrives in daytime temperatures up to 40°C (Ebert et al., 2011), so maximum temperature increase is desirable for producing amaranth in the northeastern U.S., and excessive temperature

is likely not an issue. Access of pollinators is often a consideration for crops in a protected agriculture system, but this is not an obstacle for leafy green vegetables like amaranth. Amaranth is, however, very fast-growing and harvested around three weeks after transplant (Ebert et al., 2011). Labor input for construction and removal of low tunnels would therefore be a frequent cost, even if plants do not outgrow the tunnels and no access to the crops for maintenance is required during the growing period. Lastly, it should be noted that amaranths are not the high value crops typically used as reference in economic analyses of plasticulture systems (Blomgren and Fisch, 2007; Waterer, 2003; Wells, 1996; Wells and Loy, 1993). Especially in the case of high tunnels, intercropping or multiple cropping with higher value crops holds potential for maximizing profits in plasticulture amaranth production. However, this strategy would likely require some compromise on temperature to ensure no damage to additional crops.

CHAPTER 3

Chapter 3 has been formatted for submission to HortTechnology.

Vegetable Amaranth (*Amaranthus* spp.) Variety Trials in the Northeastern United States

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Subject Category: Variety Trials

Vegetable Amaranth (*Amaranthus* spp.) Variety Trials in the Northeastern United States

Summary. In 2016, ten vegetable amaranth (*Amaranthus* spp.) varieties were evaluated for suitability for plasticulture production in the northeastern temperate climate. Yield, CV, and leaf to stem ratios were reported for the eight *A. tricolor*, one *A. viridis*, and one *A. hybridus* varieties. All plants were grown using drip irrigation and black plastic mulch under 0.8-mil clear slitted low tunnels. Ten plants of each variety were tested in a randomized complete block design with four replications; the study was repeated seven times over the season, but the seventh planting was excluded from analyses due to frost damage. There was a significant interaction of planting date and variety on yield, but some varieties were consistently high-yielding. ‘Green Pointed Leaf’ and ‘Miriah’ had the greatest yields overall, were in the highest yielding group in every planting, and were notably high-yielding in the early- and late-season. The effect of variety on yield was reduced in the high ambient temperatures of mid-summer. ‘Green Callaloo’ was high yielding with poor leaf to stem ratio; a dwarf variety, ‘White Leaf,’ was low yielding but excelled in leaf to stem ratio. ‘Red Callaloo’ and ‘Red Garnet’ tended to have consistently low yields, and generally low but variable leaf to stem ratios. Production and marketing strategies to be considered in addition to performance measures are discussed.

Ethnic crop production has received increased attention as an opportunity for farmers to expand into underserved markets. These markets are significant in the northeastern United States, and small farms with flexible, diversified production are ideally positioned to serve these markets (Mangan et al., 2008). Amaranth (*Amaranthus* spp.) is eaten as a vegetable in over 50 countries worldwide, boasts a remarkable nutritional profile, and is regarded as easy to grow and resilient (National Research Council, 2006). Amaranth may offer wide familiarity to many regular buyers of ethnic produce; an appealing option for health-conscious buyers of novel produce; and a low-maintenance addition to small farms seeking sustainability through diversified production. Amaranth varieties, however, are far less developed than many more common vegetables, and little intensive production research has taken place in the United States.

The USDA Economic Research Service has identified increased diversity of the U.S. population as one of the three most important influences on future U.S. food markets (Ballenger and Blaylock, 2003). Ethnic crop production and marketing studies in the northeastern region have found that regular ethnic produce buyers are eager to buy more of their traditional produce locally. The advantages of engagement with this market outweigh the production challenges of growing heat-loving ethnic crops in the northeastern temperate climate (Govindasamy et al., 2006; Govindasamy et al., 2007; Mangan et al., 2008; Sciarappa et al., 2016).

Amaranth is especially sensitive to temperature and low relative humidity, making long-distance shipping challenging (Wheeler et al., 2015). Competition from imports is therefore minimal, and amaranth is a strong candidate for fresh, direct to consumer

sale. In New England, the percentage of farms that engage in direct to consumer sales, and the proportional contribution of these sales to the total agriculture market, are roughly five times that of the United States as a whole (NASS, 2012). These direct sale systems allow growers to connect with customers who tend to value both variety and high nutritional value; the potential for increased customer loyalty and value-added pricing in these systems is especially important for the viability of small, diversified farms (Bond et al., 2009). Amaranth leaves are high in protein, β -carotene, iron, calcium, vitamin C, and folic acid (Achigan-Dako et al., 2014). They have also been rated comparably to spinach in sensory evaluations (Abbott and Campbell, 1982). They may therefore lend well to marketing as a substitute for more common greens, even for customers who do not regularly buy ethnic produce.

Along with expansion into new markets and offering variety to existing customers, diversified production is important to mitigating risk for many small farmers (Sassenrath et al., 2010). Amaranth has been reported to be resistant to many biotic and abiotic stresses, so its production in a diversified small farming system could contribute to farm resilience and sustainability. However, many ethnic crops may be unfamiliar to growers, not traditionally grown in the region, or simply understudied for intensive production. Region-specific production protocols and variety recommendations are necessary for growers to successfully realize the on-farm and market-based benefits of increased diversity (Mangan et al., 2008).

Amaranth's wide distribution through both tropical and temperate climates is largely due to its C4 photosynthetic pathway that allows efficient use of CO₂ in variable environmental conditions (Stallknecht and Schulz-Schaeffer, 1993); amaranth's

tolerance of marginal soils, high heat, and moisture stress are well accepted, but exploration of these qualities as they relate to intensive production is lacking. Because it thrives in high heat, amaranth received some attention from researchers as a potential summer greens substitute in the Southern U.S. (Makus, 1984; Sealy et al., 1990; Whitehead and Singh, 2002). However, the few evaluations of amaranth in temperate climates suggest that varieties with the highest yield potential in optimal environmental conditions may also be the most susceptible to wetter, cooler conditions (Campbell and Abbott, 1982; Wu et al., 2002).

Because these sub-optimal conditions characterize much of the early growing season in the northeastern U.S., reliance on variety recommendations from warmer climates may not be feasible; varieties resistant to environmental fluctuation may be the best candidates for regional production. Variety recommendations in the Northeast also need to acknowledge common regional production practices, such as transplanting. Some growers' guides suggest that not all amaranth species tolerate transplanting (Ebert et al., 2011), but no primary studies on transplant response have been conducted.

This study evaluated ten vegetable amaranth varieties for production in the northeastern temperate climate, with a focus on the realities of regional small farms. Plants were greenhouse-started and transplanted to a low tunnel system, two techniques commonly used to enhance yields and extend the season of heat-loving crops. Seven planting dates over the 2016 growing season allowed for observation of plant performance in both early and late growing seasons. Low fertilizer inputs and

drip irrigation allowed for evaluation of these varieties as a low-cost addition to existing small farm production.

Materials and Methods

Research Site. Research was conducted during the 2016 growing season in an organically-managed field at the University of Rhode Island Greene H. Gardener Agricultural Experiment Station in Kingston, RI. The soil type is Bridgehampton silt loam with a 0-3% slope. Double rows of drip-tape were laid 12 inches apart under 1-mil embossed black plastic mulch in 30-inch wide north-south oriented raised beds. Based on soil test results and findings that amaranth responds well to organic forms of Nitrogen (N) (AdeOluwa et al., 2009; Edomwonyi and Opeyemi, 2009; Makinde, 2015), the area was fertilized with Pro-Gro Organic Fertilizer 5-3-4 (North Country Organics, Bedford, VT). The application rate was 50 lb/A of N at the time of bed preparation. Vegetable amaranth fertility studies have reported a positive yield response to N application rates up to 135 kg/ha (120 lb/A) (Singh and Whitehead, 1996), but Onyango et al. (2012) found the positive response to be largely saturated at 20 kg/ha (18 lb/A) of N. The conservative rate of N application used for this study reflects a desire to minimize nitrate accumulation and evaluate varieties for low-input, low-cost commercial production.

Varieties. Ten amaranth varieties were included the study. Most were *A. tricolor*, the most popular and widely available vegetable amaranth species. *A. tricolor* varieties were ‘Asia Red,’ ‘Green Pointed Leaf,’ ‘Red Stripe Leaf,’ ‘Southern Red,’ (Evergreen Seeds, Anaheim, CA), ‘Red Garnet,’ ‘White Leaf,’ (Kitazawa Seed Co., Oakland, CA), ‘Miriah,’ and ‘Red Callaloo,’ (Baker Creek Heirloom Seed Co., Mansfield, MO).

‘Green Callaloo’ (Baker Creek Heirloom Seed Co., Mansfield, MO) is a variety of *A. viridis*, commonly eaten in Caribbean and some African cultures. Members of the African Alliance of Rhode Island (AARI) provided seeds of one heirloom variety, which we called ‘Mchicha’ and identified as *A. hybridus*. The AARI members grew *mchicha* (meaning ‘amaranth’ in Swahili) in Burundi, and now grow both a large-leaf and a small-leaf variety in Providence, RI. The small-leaf variety was not included in the study due to a shortage of seeds. Three commercially-available varieties of *A. tricolor* were also obtained but eliminated from the study due to poor germination rates in two initial germination tests.

Culture and Design. All seeds were green-house started in 50-count cell trays, using Metro-Mix 830 soil (SunGro, Agawam, MA) covered with a thin layer of vermiculite. The greenhouse was set to heat at 70°F and cool by way of passive ventilation at 74°F. No supplemental light was used in the greenhouse. All varieties were seeded every two weeks and transplanted to the experiment site roughly two weeks later. Plots were arranged in a randomized complete block design, with ten plants of each variety and four replicates. Each block was a raised bed with double rows 12 inches apart. Plants were spaced 12 inches apart within the rows.

Directly after transplanting, low tunnels were constructed over the raised beds using galvanized metal hoops and 0.8-mil clear slitted plastic. Hoops were placed five feet apart from each other with a center height of three feet. Plastic was laid over hoops and staked down at the ends and along the sides of each tunnel. Lastly, a second set of hoops were driven into the ground over the plastic. Sandbags were used to further weigh down plastic on the sides of tunnels during times of heavy winds. Plots were

irrigated as needed, and weeds were controlled by mulching with woodchips between rows and hand-pulling when necessary. Plots were regularly monitored for pests, with the only intervention being a one-time application of PyGanic (MGK, Minneapolis, MN) to control Striped Blister Beetles (*Epicauta vittata*) on 14 July.

Harvest. Amaranth can be harvested repeatedly by cutting the main stem or harvesting individual leaves. For single harvest, whole plants are commonly pulled and sold as a bundle, including roots (Ebert et al., 2011). Repeat harvest can delay flowering, but this study used single harvest in order to observe flowering behavior. Rather than including roots in yield calculations, plants were harvested by cutting directly above the soil surface. Plants were harvested at the early flowering stage, similar to the methods used in amaranth variety trials by Campbell and Abbott (1982).

Data Collection and Analysis. Plants were weighed immediately after harvest. After fresh weights were recorded, stems and leaves of a random two-plant sub-sample were separated and dried at 110°F until they reached a constant weight. Dried leaf and stem weights were used to calculate a leaf to stem ratio, which we expressed as the leaf-percentage of total dry weight.

The analysis of variance functions (ANOVA) in R Version 3.2.3 (R Core Team, Vienna Austria, 2015) were used to test for effects and interactions of variety and planting date on both yield and leaf to stem ratio. Tukey's HSD test was used for means separation. All tests were performed at $p < 0.05$ significance level. Pearson's test of correlation was used to determine the correlation between fresh weight and dried leaf to stem ratio. Coefficients of variation (CV) were calculated as a measure of

yield stability. CV is the square root of a variety's all-season variance, divided by the grand mean yield of the variety, then multiplied by 100 and expressed as a percentage.

Results

Growth Period. The varieties clearly split into two distinct groups, with 'Red Garnet,' 'Red Callaloo,' 'Green Callaloo,' 'Red Stripe Leaf,' 'Miriah,' 'Mchicha,' and 'Green Pointed Leaf' consistently being ready for harvest earlier than 'Asia Red,' 'Southern Red,' and 'White Leaf.' An exception to these groupings was made in the sixth planting; many of the 'Red Garnet' and 'Red Callaloo' stems were broken in a storm, and these varieties were harvested with the second group. The seventh and final planting had the longest time to harvest, and plants were frost damaged before the second group was harvested. Consequently, only results from the first six plantings are included in our analyses. Seeding and harvest dates are listed in Table 1.

Table 1. Production dates for seven 2016 vegetable amaranth plantings.

Seed date	Transplant date	Harvest group 1 ^z	Harvest group 2 ^y
15 May	1 June	24 June	29 June
28 May	13 June	7 July	14 July
12 June	27 June	22 July	27 July
30 June	18 July	14 Aug	16 Aug
14 July	29 July	22 Aug	25 Aug
2 Aug	16 Aug	14 Sep	21 Sep
17 Aug	1 Sep	5 Oct	---

Yield. There was a significant variety by planting date interaction for yields ($p < 0.0001$). Consequently, variety effects for each planting date were analyzed separately, and the effect of planting date was analyzed separately for each variety. Yields of each variety over six planting dates are shown in Fig. 1.

Figure 1. Average yield for ten vegetable amaranth varieties in six in 2016 plantings. Yields shown are the averages of four replicates. Bars represent $\pm$ one standard error. (1 kg = 2.205 lb)

Variety Effects. ‘Miriah’ and ‘Green Pointed Leaf’ had the highest and second highest average yields for the experiment in total and did not vary significantly from one another in any planting date. Except for ‘Miriah’ yielding significantly more than ‘Red Stripe Leaf’ in the sixth planting date, the top performing varieties (‘Miriah,’ ‘Green Pointed Leaf,’ ‘Green Callaloo,’ ‘Southern Red,’ ‘Mchicha,’ and ‘Red Stripe’) had statistically equal yields for the last five out of the six plantings dates. There was greater variation among this group in the first planting, where ‘Green Pointed Leaf’ yields were significantly greater than ‘Southern Red;’ and ‘Mchicha’ yields were significantly less than ‘Miriah,’ ‘Green Pointed Leaf,’ and ‘Red Stripe Leaf.’

‘Red Callaloo’ and ‘Red Garnet’ had the lowest average yields for the experiment as a whole and did not vary significantly from one another in any planting. However, ‘Red Callaloo’ yields were statistically equal to all other varieties in the second, third, and fourth planting. ‘Red Callaloo’ only yielded significantly less than the top three performers (‘Green Pointed Leaf,’ ‘Miriah,’ and ‘Red Stripe Leaf’) in the first planting and the top two performers (‘Miriah’ and ‘Green Callaloo’) in the sixth planting. ‘Red Garnet’ yield comparisons to higher yielding varieties were significant more often. The treatment effect of variety on yield was the greatest in the first planting. In the third planting, all varieties except ‘Asia Red’ had statistically equal yields.

Planting Date Effects. Yields of replicates within varieties were the most variable in the first planting. Combined average yields for all varieties were greatest in the fourth, fifth, and sixth plantings; the second planting had the lowest combined average yields. There was not a significant effect of planting date on yield for ‘Green Pointed Leaf,’ ‘Red Callaloo,’ ‘Southern Red,’ or ‘White Leaf.’

Leaf to Stem Ratio. There was a significant variety by planting date interaction effect on leaf to stem ratio ($p < 0.0001$). There was not a strong correlation of yield and leaf-percent of total dry weight ($r = 0.036$). Leaf to stem ratios are presented in Fig. 2.

‘White Leaf’ was a stand-out performer in leaf to stem ratio, with the highest leaf-percent of total dry weight in every planting. The average leaf-percent of ‘White Leaf’ over the entire experiment was 81.99% of total dry weight. It was significantly higher than all varieties in the second and fourth plantings. However, ‘White Leaf’ leaf-percent did not differ significantly from ‘Miriah’ in the first, third, and fifth plantings; from ‘Red Stripe Leaf’ in the third, fifth, and sixth plantings; or from ‘Asia Red’ in the sixth planting. ‘Asia Red’ and ‘Miriah’ had the second and third highest leaf-percent averages over the entire experiment, at 70.47% and 69.20% respectively. ‘Red Garnet,’ ‘Red Callaloo,’ and ‘Green Callaloo’ consistently had the lowest leaf to stem ratios. In the first five plantings, all three had significantly lower leaf-percentages than a majority of the varieties tested.

‘Green Callaloo,’ ‘Mchicha,’ ‘Southern Red,’ and ‘Red Stripe,’ leaf to stem ratios were not significantly affected by planting date. The range of all-season average leaf-percentages was 42.21% (‘Green Callaloo’) to 81.99% (‘White Leaf’).

Figure 2. Average leaf-fraction of total dry weight of all varieties in 2016. Results are averages of four replicates. Bars represent $\pm$ one standard error.

CV. ‘White Leaf’ had the lowest CV at 21.33%, followed closely by ‘Southern Red’ and ‘Green Callaloo,’ both under 22%. ‘Asia Red’ had the highest CV at 35.81%, and ‘Red Stripe Leaf’ had the second highest at 31.38%. Fig. 3 shows variety CVs on the x-axis with variety grand mean yields on the y-axis. Varieties in the upper left quadrant depict varieties with both low CV values and high yields.

Figure 3. Average plant yields for all of the 2016 growing season plotted against coefficients of variation (CV)^z for each variety.

(1 kg = 2.205 lb)

^z square root of variety variance across planting dates, divided by the overall mean yield of the variety, and multiplied by 100.

Discussion

Yield Findings Comparisons. Although our variety ‘Mchicha’ is not commercially available, *A. hybridus* was similarly a top performing species in Mississippi (Igbokwe, 1988), Texas (Sealy et al., 1990), and Georgia (Singh and Whitehead, 1996).

However, these climates are markedly warmer than that of Rhode Island, and the top accessions in all three studies originated in Greece. Wu et al. (2002) tested 29 *A. hybridus* accessions, including one from Greece; three accessions from Zambia and 12 from Zimbabwe, locations which may be more comparable to our ‘Mchicha’ variety

from Burundi, were also tested. Accessions were evaluated in tropical and temperate climate plots, and accessions from different origins tended to respond differently in each. The *A. hybridus* from Greece performed best in tropical climate plots, but on the whole, *A. hybridus* was one of the highest yielding species in the temperate climate plot (Wu et al., 2002). *A. hybridus* is actually defined by high genetic diversity; it is the progenitor of closely related species that have undergone more intense selection (Achigan-Dako, et al., 2014). While this diversity may well contribute to the broadly positive evaluations of *A. hybridus*, it also makes it somewhat difficult to generalize results pertaining to the species.

Wu et al. (2002) also tested three accessions of *A. viridis*, which was the top yielding variety in tropical plots. *A. viridis* yielded less in temperate plots, but the species was rated highly adaptable and disease resistant in both climates (Wu et al., 2002). Our *A. viridis* variety, ‘Green Callaloo,’ was also in the top yielding group.

Our results can be more directly compared to those of Maynard (2013), who tested some of the same varieties (‘Asia Red,’ ‘Green Pointed Leaf,’ ‘Red Stripe Leaf,’ and ‘White Leaf’) in a comparable climate in Connecticut. Although Maynard (2013) used repeat harvest, rather than single, our findings that ‘White Leaf’ consistently yielded significantly less than most other varieties confirm those of Maynard (2013). ‘Asia Red’ exhibited highly variable yields in our study; Maynard (2013), similarly, reported moderate yields overall and statistically equal yields to both highest and lowest yielding varieties in different plantings. Our findings also compare favorably with those of Maynard (2013) in some top yielding varieties: ‘Green Pointed Leaf’ was our highest yielding variety overall, but yields did not differ significantly from ‘Red Stripe

Leaf” in any planting. Maynard (2013) found ‘Red Stripe Leaf’ yielded more than ‘Green Pointed Leaf’ in all plantings at two locations, but the yields also showed no significant difference.

Photothermal Characteristics and Yield. Day-length sensitivity in amaranth is not well understood. There are mixed reports of day-length requirements, and the magnitude of day-length sensitivity may be influenced by other environmental factors and cultural practices (Achigan-Dako et al., 2014; Atherton, 1987; Holm et al., 1997; Kulakow and Jain, 1985). Wu et al. (2002) observed that *A. viridis*, *A. tricolor*, and African populations of *A. hybridus*, all had greater variation in mean growth period in temperate climates than in tropical. Our range of transplant-to-harvest days, determined by bud formation, was 23-29 days for the first harvest group and 27-36 days for the second harvest group (Table 1).

There were significant yield differences within each harvest group in every planting. However, because these varieties represent such a range of growth habits and sizes, dissimilar yields may not exclude similar photothermal responses. There was less variability in flowering time for the first harvest group, yet more significant yield differences across plantings. There was more variability in days-to-harvest for the second harvest group, yet the yields of these varieties were not affected by planting date. It is possible that flowering for the second harvest group may be closely linked to plant growth, and given the especially long growth period in the sixth planting, it is possible that the contribution of accumulated day-light hours to growth rate is greater in these varieties. Flowering does not seem to be strongly linked to day-length for any of these varieties.

Performance Measures. Although average yield influences CV, consideration of both yield and CV may be most useful in evaluating variety performance. Leaf to stem ratio is a valuable variety descriptor, but is not an unqualified measure of variety desirability. For an accurate reflection of variety performance, these parameters should all be weighed against one another; for ideal variety selection, production strategy and target customer base may play an equal role.

Variety CVs are useful in avoiding an artificially high estimation of varieties that exhibit high yield potential, rather than reliably high yields. This may be especially important to vegetable amaranth growers in the northeastern U.S. because temperatures for much of the growing season may be sub-optimal for amaranth. Top performing varieties in optimal conditions may be more affected by the cooler, wetter conditions of the early growing season in the northeastern U.S. (Campbell and Abbott, 1982). Varieties with reliable yields over the whole season may therefore be more desirable than varieties with the highest yield potential.

‘Green Pointed Leaf,’ was one of the two highest yielding varieties over all. Consequently, its relatively high CV (29.90%, third highest of the varieties tested) is due to high variability across plantings (Fig. 3). However, in the third planting, when ‘Green Pointed Leaf’ average yield was the lowest of the season, it was still greater than two-thirds of the varieties tested and statistically equal to the top yielding varieties. Furthermore, the greatest departure from the overall mean yield of ‘Green Pointed Leaf’ was especially high yields in the first planting; 50% of the varieties had their lowest yields of the experiment in the first planting, and ‘Green Pointed Leaf’

yields were nearly double the yields of those varieties. In short, yield potential may indeed be great enough to trump stability in this case.

‘Miriah,’ ‘Mchicha,’ ‘Southern Red,’ and ‘Green Callaloo’ all had high yields and low CVs (Fig. 3), indicating they are likely desirable varieties. However, ‘Green Callaloo’ and ‘Southern Red’ both had low leaf to stem ratios, at 42.21% and 54.92% of dry weight, respectively, which may be considered less desirable (Fig. 2). Campbell and Abbott (1982) found that leaf to stem ratio was negatively correlated to yield, or that the varieties with the highest fresh weights tended to be the most stem-heavy. For the varieties tested here, no relationship between leaf to stem ratio and yield was observed ($r^2 = 0.0013$), but ‘Red Callaloo’ and ‘Red Garnet’ had the lowest average leaf to stem ratios and the lowest average yields overall.

Production Strategies and Intended Market. Production strategy was standardized in this study for ease of comparison. However, targeted production strategies for individual varieties could positively influence plant performance and increase yield per production area. Additionally, quantitative performance measures may be qualified by intended market and use. For example, ‘White Leaf’ had the third lowest average yields over the experiment, with average yield around 60% of the highest yielding varieties. However, ‘White Leaf’ is a dwarf variety, making direct yield comparisons with the other varieties inappropriate. ‘White Leaf’ had the lowest CV of all varieties tested (21.33%) and the greatest leaf to stem ratio by far (81.99% of total dry weight). Growers may consider a higher planting density than was used in this study, or even polyculture with taller crops. Its dense, bushy habit lends most easily to single harvest

or harvesting of individual leaves, and its tender leaves may be marketable as a substitute for more common salad components.

Conversely, ‘Red Callaloo,’ ‘Red Garnet,’ and ‘Green Callaloo’ had the three lowest overall leaf to stem ratios. However, the traditional Caribbean dish *Callaloo* makes use of both stems and leaves, as do many cooked amaranth dishes around the world.

‘Red Callaloo’ and ‘Red Garnet’ also had low yields, but their tall, stemmy habit may lend to repeat harvest, rather than single. Repeat harvest is commonly used to increase branching and delay flowering in amaranth production, and we observed increased branching in our study after accidental stem breakage from a storm in the sixth planting. ‘Red Callaloo’ had a substantial increase in leaf-percent for the sixth planting; ‘Red Garnet’s leaf-percent was roughly equal to its highest reported leaf-percent of the first planting. If growers choose to grow a ‘Callaloo’ variety for its familiarity to a chosen customer base, they could use increased planting density and frequent harvests to increase overall yields and likely leaf to stem ratio.

The fact that Maynard (2013) reported high yields from ‘Red Stripe Leaf’ and ‘Green Pointed Leaf’ with repeat harvest, as did we with single harvest, indicates growers could opt for either strategy with these varieties. ‘Green Pointed Leaf,’ ‘Miriah’ and ‘Red Stripe Leaf’ had the highest leaf to stem ratios, after ‘White Leaf.’ Smaller leaves obtained from repeat harvest could be marketed as raw greens, or more mature leaves as cooked greens substitutes.

Variety Recommendations. Average yields across varieties were most similar in the third planting. Compared to the average of the second through fifth plantings, the mean square of variety differences was around five times greater in the first planting,

and about 3.5 times greater in the sixth planting. These trends suggest that variety selection becomes less important for yield in the hottest summer months in the northeastern U.S. Growers may want to select from the following recommended varieties based on perceived customer preferences, be they cultural or aesthetic. ‘Green Callaloo’ is a high-yielding, reliable variety for which we recommend repeat harvest to improve leaf to stem ratio. ‘Miriah’ and ‘Red Stripe Leaf’ both have striking flashes of red on their leaves, which is one of the more common and recognizable appearances of *A. tricolor*. These varieties may be especially aesthetically appealing to customers who are unfamiliar with amaranth. Although ‘Miriah’ has a higher CV than ‘Red Stripe Leaf,’ much of ‘Miriah’s variation was due to especially high yields in the first and last planting, and it still outperformed most varieties in every planting. Consequently, between these two very similar varieties, ‘Miriah’ is our first recommendation. ‘White Leaf’ is reliable and leafy, and increased planting density can balance lower yields per plant. Our findings that the top yielding varieties in the more variable first and last plantings were also high performers all season make ‘Miriah’ and ‘Green Pointed Leaf’ clear choices for a long, productive season in the northeastern temperate climate. Although ‘Mchicha’ is not a commercially available variety, our findings suggest that further investigation and development of *A. hybridus* varieties may also be promising.

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CHAPTER 4

Chapter 4 has been formatted for submission to HortTechnology.

Evaluation of Plasticulture Production Systems for Vegetable Amaranth (*Amaranthus spp.*) in the Northeastern United States

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Evaluation of Plasticulture Production Systems for Vegetable Amaranth (*Amaranthus spp.*) in the Northeastern United States

Summary. Two *A. tricolor* vegetable amaranth varieties, ‘Green Pointed Leaf’ and ‘Red Stripe Leaf,’ were grown in four production systems in Kingston, RI in 2016. The systems were 1) gothic-style high tunnel covered in a double, inflated layer of 6-mil 4-year Tufflite greenhouse plastic, ventilated for polyculture with tomatoes; 2) low tunnels constructed with 0.8-mil clear slitted plastic and galvanized metal hoops over raised beds with black plastic mulch; 3) raised beds with black plastic mulch; and 4) bare soil. All plots used drip irrigation and greenhouse-started transplants. A split-plot design with 10 plants in each plot and four replicates was repeated three times over the season. High tunnel plots were excluded from the second planting due to Woodchuck (*Marmota Monax*) damage. Low tunnel plots had the greatest yields in every planting. The magnitude of production system effects decreased as ambient temperatures increased throughout the season. Rankings of yields from the four production systems were consistent in each experiment. Yield rankings from greatest to least were: low tunnel, black plastic mulch, high tunnel (when present), and bare soil. Leaf to stem ratios of a two-plant subsample were calculated and did not appear to be influenced by production system, despite occasional significant differences.

The USDA Economic Research Service has identified the increasing diversity of the U.S. population as one of the most important influences on future U.S. food markets (Ballenger and Blaylock, 2003). In 2015, over 13% of the U.S. population was born outside of the U.S.; immigrants and their U.S.-born family members comprised 27% of the total U.S. population (U.S. Census Bureau, 2015). Ethnic crop marketing studies in the northeastern U.S. have found that ethnic produce buyers are willing to pay premium prices and adjust shopping patterns based on the freshness and availability of their traditional produce. Amaranth leaves are eaten in cultures ranging from South America to Africa to Eastern Asia, and regional studies have confirmed its appeal to many of the fastest-growing ethnic populations in the northeastern U.S. (Govindasamy et al., 2006; Govindasamy et al., 2007; Sciarappa et al., 2016). Ethnic crop production studies have found that many tropical and sub-tropical crops are easily produced in the northeastern temperate climate. However, these studies emphasize that region-specific production and marketing research will be fundamental to the success of growers in incorporating potentially unfamiliar crops (Mangan et al., 2008; Sciarappa et al., 2016). Amaranth has a C4 photosynthetic pathway, which is rare in dicots. The biological traits that accompany C4 photosynthesis have made amaranth an important crop in tropical and subtropical regions; amaranth is able to use CO₂ efficiently under moisture and heat stress (Achigan-Dako et al., 2014). However, these traits are contradictory to those of many greens commonly grown in the northeastern U.S. Popular vegetable amaranth species thrive in temperatures up to 40°C (104°F), do not

tolerate temperatures below 15°C (59°F), and have substantially higher light saturation points than common spring and fall greens (Ebert et al., 2011).

The components of plasticulture systems, including plastic mulches, drip irrigation, and crop covers, are valuable tools for extending the season and enhancing yields of warm-weather crops in the northeastern region (Wells and Loy, 1993). Black plastic mulch increases soil temperatures and can improve resource use efficiency; fertilizer leaching, evaporative water loss, and competition for resources from weed growth are all reduced under plastic mulch. Various forms of crop covers are used for their heating effects and provide the added benefit of enhanced crop protection from the elements and pests. When crop covers are used in addition to black plastic mulch, the effects of both components are amplified (Tanner, 1974).

There is substantial room for variation in plasticulture system design; each structural and material combination results in varying levels of protection, microclimate effect, permanence, accessibility, and cost. For crop covers, low tunnels (row covers) and high tunnels represent the spectrum of these considerations. Studies suggest both systems are economically viable options for northeastern growers. However, target crops, production area, and markets should be the deciding factors in plasticulture design decisions, especially for small and beginning farmers (Wells and Loy, 1993).

The low tunnels used in this study were constructed with galvanized metal hoops covered with 0.8-mil clear slitted plastic. Early low tunnel technologies, designed to provide maximum frost protection, required daily manual ventilation. The development of breathable cover materials reduced the need for ventilation, but light transmission was also reduced. Because amaranth has a high light saturation point,

reduced light transmission would limit amaranth's photosynthetic capacity. Clear slitted plastic combines high light transmission and self-ventilation. These covers cannot combat extreme temperatures at night; however, continually intact slitted tunnels accumulate more heat units over time than tunnels that must be removed during the day. Heat unit accumulation, often measured in growing degree days (GDD), is directly linked to the growth of many warm-weather crops. However, low tunnels perform this function so effectively that excessively high temperatures within tunnels becomes a concern for many crops in high ambient temperatures (Wells and Loy, 1985a; Wells and Loy, 1985b; Wells and Loy, 1993).

The required low tunnel materials are relatively inexpensive, but it is difficult to reuse plastic without compromising light transmission or structural integrity. A low initial investment is tempered over time by repeated material cost, as well as the corresponding labor cost of tunnel construction and removal. Any low tunnel crop maintenance beyond irrigation and fertigation requires removal of the plastic, which interrupts heat accumulation (Waterer, 2003).

Although there are numerous variables associated with high tunnel design, a typical design resembles a greenhouse frame covered in 4- to 6-mil plastic. Ventilation is provided by rolling up and securing the plastic on the sides of the tunnel. High tunnels typically span multiple rows of crops and, once constructed, provide excellent protection from the elements and effortless access to crops for harvest or maintenance. High tunnels are considered temporary structures, but plastic may be used for multiple seasons, and frames are even longer lasting (Wells and Loy, 1993; Wells, 1996). The rise in popularity of high tunnels in the U.S. is in large part due to findings that initial

investments can reliably be recovered when growing high value crops (Carey et al., 2009; Lamont, Jr., 2009). Furthermore, the NRCS Environmental Quality Incentives Program (EQIP), which provides financial support for the implementation of conservation practices, has been assisting growers with high tunnel construction costs since 2010; the EQIP High Tunnel initiative is now active in all 50 states (NRCS, 2017).

Understandably, economic analyses of these systems have focused on high value crops, rather than leafy greens like amaranth. Amaranth's relatively short time to harvest and affinity for high heat also warrant special consideration in plasticulture design decisions. This study evaluated the benefit of three plasticulture systems in comparison to bare soil production of amaranth: black plastic mulch (with no crop cover), low tunnel with black plastic mulch, and high tunnel with no mulch. Black plastic mulch was selected to represent the most basic plasticulture system. Black plastic mulch and drip irrigation have been used successfully for intensive Amaranth production studies in Maryland (Meyers et al., 2001) and New Jersey (Sciarappa et al., 2016), but production system comparison was not the focus of these studies. Low tunnels combined with black plastic mulch were selected to provide maximum heat accumulation. Given Rhode Island's temperate climate and amaranth's high temperature needs, excessive heat was not an issue. However, amaranth's short time to harvest necessitates fairly frequent tunnel construction and removal, crop maintenance notwithstanding. Acknowledging that amaranth monoculture in high tunnels is not the most profitable use of these structures for growers, the high tunnel treatment was selected to evaluate amaranth as an addition to existing high tunnel production. While

there is potential for very high heat accumulation within high tunnels, growers control temperatures through ventilation. Our high tunnel system followed ventilation protocols for tomatoes, which were listed as a primary high tunnel crop in many of the 50 states in a nation-wide survey of extension agents (Carey et al., 2009).

Materials and Methods

Research Site. Research was conducted during the 2016 growing season at the University of Rhode Island Greene H. Gardener Agricultural Experiment Station in Kingston, RI. The soil type is Bridgehampton silt loam. Kingston is located at 41°N latitude. In June, July, and August, average daily temperatures in Kingston range from 67- 72°F; average minimum temperatures are 55°-60°F; and average maximum temperatures are 78-83°F. The 2016 growing season was generally hotter and drier than historical averages. These months received 5.2 inches of precipitation in 2016, compared to the historical average of 12.3 inches. The greatest departure from historical temperatures was in August, when the average maximum temperature was 4.4°F higher, and the average daily temperature was 3.1°F higher (NOAA, 2017).

Varieties and Design. Two varieties of *A. tricolor*, the most widely available vegetable amaranth species, were used throughout the experiment: ‘Green Pointed Leaf’ and ‘Red Stripe Leaf’ (Evergreen Seeds, Anaheim, CA). Response was evaluated in four production systems: high tunnel, low tunnel with black plastic mulch, black plastic mulch (uncovered), and bare soil. The production systems were main plot factors in a split-plot design with four replications. Full randomization of the production systems was not possible because we used pre-constructed high tunnels. The varieties were subplot factors and were randomized within each main plot. Each experimental plot

consisted of 10 plants; the experiment was repeated three times over the season.

Production dates are presented in Table 1.

Table 1. Seeding transplant, and harvest dates for three vegetable amaranth plantings in 2016.

Planting	Seed	Transplant	Harvest
1	22 May	10 Jun	6 July
2	16 June	6 Jul	1 Aug
3	11 July	1 Aug	26 Aug

Culture. All plants were greenhouse-started in 50-count cell trays using Metro-Mix 830 (SunGro, Agawam, MA). The greenhouse was set to heat at 70°F and to cool by way of passive ventilation at 74°F; no supplemental light was used. All

planting beds were 30 inches wide and irrigated as needed using drip tape with 12-inch emitter spacing (Aqua Traxx, Bloomington, MN). Plants were spaced 12 inches apart within double rows. Based on soil test results and reported positive response of amaranth to organic Nitrogen (N) sources (AdeOluwa et al., 2009; Edomwonyi and Opeyemi, 2009; Makinde, 2015), all plots were fertilized with Pro-Gro Organic Fertilizer 5-3-4 (North Country Organics, Bedford, VT) at 50 lb/A of N once before transplanting. This conservative application rate was chosen to balance positive yield response with mitigation of cost and nitrate accumulation.

High Tunnel System. The high tunnel plots were within an east-west oriented gothic-style high tunnel measuring 21 ft x 72 ft with a sidewall height of 4 ft and a peak center height of 13 ft. The high tunnel frame was covered in a double, inflated layer of 6-mil 4-year Tufflite IV greenhouse plastic (Berry Plastics Corp., Evansville, IN). An automated vent at the top of the tunnel (Nolt's Produce Supplies, Leola, PA) was set to

open at 90°F; ventilation was also provided by rolling up the sides of the high tunnels to the sidewall height of four feet. The ventilation procedures were those used for tomatoes, which were also growing in the high tunnel. Plants were transplanted directly into tilled soil. Weed pressure is low in high tunnels; weeds were controlled by hand-pulling when necessary.

Low Tunnel System. The low tunnel plots began with north-south oriented raised beds, covered in 1-mil embossed black plastic mulch. Tunnels were constructed immediately after transplant, using clear slitted 0.8-mil plastic and galvanized metal hoops. Hoops were placed five feet apart over raised beds with a center height of three feet. Hoops were covered with plastic, and a second set of hoops was laid over the plastic. Plastic was staked down at the ends and along the sides of the tunnels. Sandbags were also used along the sides of the tunnels in times of high winds. Woodchips were used to mulch between rows.

Plastic Mulch and Bare Soil Systems. Plastic mulch plots consisted of north-south oriented raised beds covered in 1-mil embossed black plastic mulch. In bare soil plots, plants were transplanted directly into tilled soil in north-south oriented beds. Woodchips were used to mulch between rows, and weeds were controlled by hand-pulling within rows.

Pest Management. Woodchuck (*Marmota monax*) damage to the plants in the high tunnels was so severe for the second planting that harvest totals were not collected. To avoid damage to the third planting, high tunnel plots were covered with ProtekNet (Dubois Agrinovation, Quebec, Canada), laid over galvanized metal hoops, directly after transplanting. Additionally, an egg- and garlic-based repellent, Liquid Fence

(Spectrum Brands, Earth City, MO), was sprayed around the perimeter of the high tunnel. A one-time application of PyGanic (MGK, Minneapolis, MN) was used to control Striped Blister Beetles (*Epicauta vittata*) on 14 July in the low tunnel, black plastic mulch, and bare soil plots. Low tunnel plastic was temporarily lifted from one side of the tunnel to access plants.

Temperature Monitoring. Air and soil temperature data were logged every four hours using ThermoChron iButtons (Lawrenceburg, KY). For all plots, two soil and two air temperature sensors were placed between the two rows of plants, centered in the second and third replicates. Air temperature sensors were placed at a height of 25 cm (9.8 inches), approximating mature canopy height, and shielded from direct sunlight. Soil temperature monitors were wrapped in waterproof tape and placed at a depth of 10cm (3.9 inches). There were no plantings for which both air and both soil monitors produced data in every production system. When two datasets were available, averaged temperatures were used for analyses. The maximum variation between average temperatures recorded by replicate monitors was 0.20°C (.36°F).

Harvest and Data Collection. Plants were harvested 25-26 days after transplanting, by cutting the stem directly above the soil surface. The ten plants from a given plot were weighed together immediately after harvest to determine yield. After fresh weights were recorded, stems and leaves of a random two-plant subsample were separated and dried at 110°F until they reached a constant weight. Dried leaf and stem weights were used to calculate a leaf to stem ratio, which we expressed as the leaf-percentage of total dry weight.

Data Analysis. The analysis of variance (ANOVA) functions in R Version 3.2.3 (R Core Team, Vienna Austria, 2009) were used to determine the effects and interactions of production system and variety on both yield and leaf to stem ratio. In the cases of significant effects, Fisher's LSD test was used for means separation. All tests were performed at the $p < 0.05$ significance level. Growing degree days were calculated by subtracting a base temperature of 50°F from daily mean temperatures. Days with mean temperatures less than 50°F were given a GDD value of zero. Pearson's test of correlation was used to examine the following relationships: yield and leaf to stem ratio; yield and air growing degree days; yield and soil growing degree days.

Results

Microclimate Effects. Air and soil temperature summaries are given in Table 2. The accumulation of air and soil GDD with a base temperature of 50°F in each production system are shown in Fig. 1 and Fig. 2 respectively.

Air temperature. Low tunnels had the highest air temperatures in each planting and on average. Compared to the average bare soil air temperature, average low tunnel air temperature was 5.0°C (9.0°F) higher; average black plastic air temperature was 1.1°C (2.0°F) higher; average high tunnel air temperature was 1.6°C (2.9°F) higher. On average, low tunnels accumulated 169 more air GDD per planting than high tunnels; 189 more air GDD per planting than black plastic; and 242 more air GDD per planting than bare soil. The greatest range of air temperatures and air GDD for a single planting was in the first planting. These differences diminished as ambient temperatures rose in the second and third plantings.

Soil temperature. Black plastic plots had the highest soil temperatures on average and accumulated the most soil GDD. Compared to the average soil temperature in bare soil, average black plastic soil temperature was 5.1°C (9.2°F) higher; average low tunnel soil temperature was 3.3°C (5.9°F) higher; and average high tunnel soil temperature was 1.9°C (3.4°F) higher. On average, black plastic accumulated 247 more soil GDD per planting than bare soil and 158 more soil GDD per planting than high tunnels. Black plastic and low tunnel accumulated soil GDD differentials followed a less reliable pattern and were 127 GDD in the first planting, 59 GDD in the second planting, and 93 GDD in the third planting.

Table 2. Temperature data for four production systems. Air temperature sensors were at 25cm (9.8in) height. Soil temperature sensors were at 10cm (3.9in) depth.

$$(T(^{\circ}\text{F}) = T(^{\circ}\text{C}) \times 1.8 + 32)$$

Production method	Soil temperatures (°C)			Air temperatures (°C)		
	min	max	mean	min	max	mean
Bare soil	14.00	27.58	21.98	16.00	29.58	23.30
Black plastic	21.25	34.25	27.09	16.25	31.00	24.41
Low tunnel	18.38	30.76	25.25	20.50	37.25	28.26
High tunnel	18.42	28.75	23.85	16.00	31.17	24.90

Figure 1. Accumulation of air growing degree days (GDD) in four production method treatments in three plantings in 2016. Temperatures were recorded at a height of 25cm (9.8in). Growing degree days were calculated by subtracting a base temperature of 50°F from daily mean temperatures.

Figure 2. Accumulation of soil growing degree days (GDD) in four production method treatments in three plantings in 2016. Temperatures were recorded at a depth of 10cm (3.9in). Growing degree days were calculated by subtracting a base temperature of 50°F from daily mean temperatures.

Yield. High tunnel plots were excluded from the second planting due to severe Woodchuck damage, and each planting date was analyzed separately. There was no interaction nor main effect of variety, so the two varieties were grouped together in

yield analyses. Average yields are shown in Fig. 3. Yields displayed a similar pattern in all three plantings: low tunnel yields were the greatest, followed by black plastic mulch; high tunnel yields ranked third when present, and bare soil plots yielded the least. Although there was no difference in rank order, the magnitude of the treatment effect decreased with each planting.

Low tunnel plots produced significantly greater yields than all other treatments in the first and second plantings. In the third planting, low tunnel yields were significantly greater than all treatments except black plastic mulch. Black plastic mulch yields were significantly greater than the bare soil yields in all three plantings, and significantly greater than high tunnel yields in the first planting. However, black plastic mulch plots did not differ significantly from high tunnel plots in the third planting. High tunnel plots yielded significantly more than bare soil plots only in the first planting.

The difference between average treatment yields was greatest in in the first planting and decreased with each planting. In the first planting, average bare soil plot yield was 4% of average low tunnel yield. High tunnels, the second-lowest yielding treatment in the first planting, yielded more than the bare soil by a factor of 3.5. Average low tunnel yield was more than double that of black plastic mulch in the first planting; in the second planting, average low tunnel yield was only about 20% greater than average black plastic mulch yield. Yields were more strongly correlated accumulated air GDD ($r = 0.86$) than to accumulated soil GDD ($r = 0.75$).

Figure 3. Vegetable amaranth yields from four production systems in three 2016 plantings. High tunnel yields were not recorded in the second planting. Yields are the pooled averages of two varieties and four replicates. Bars represent $\pm$ one standard error.

(1 kg = 2.205 lb)

Leaf to Stem Ratio. Leaf-percent of total dry weight was not correlated to yield ($r = 0.06$). There was a significant effect of variety on leaf-percent of total dry weight ($p < 0.0001$), but there was no significant variety by production method or variety by planting date interaction. ‘Green Pointed Leaf’ leaf-fraction of total dry weight was 0.04 higher than that of ‘Red Stripe Leaf’, with a confidence interval of 0.02-0.06 ($p < 0.05$). There was a significant production method by planting date interaction effect on

leaf-percent of total dry weight ($p < 0.0001$), so the main effect of production system was analyzed for each planting date separately (Fig. 5). In the June planting, the low tunnel had significantly higher leaf-percent than all other treatments, which were statistically equal. In July, low tunnel leaf-percent was significantly lower than all other treatments, which were statistically equal. In August, there was no significant effect of production system on leaf-percent.

Figure 4. Leaf to stem ratios from four production systems in three 2016 plantings. Results are pooled from two varieties and four replicates. Bars represent $\pm$ one standard error.

Discussion

We observed a clear pattern in yield response to the production systems tested.

Amaranth is a heat-loving crop, and there is definite evidence of positive response to increases in soil and air temperatures. However, our treatments were production systems with effects and interactions outside of those quantified here. For example, low tunnels were the highest yielding plots. Average low tunnel air temperatures were 3.3 °C (5.9°F) higher than the second ranking high tunnel air temperatures; high tunnels ranked third in yield. Low tunnel soil temperatures, however, were second to black plastic soil temperatures by only 1.9°C (3.3°F); black plastic plots ranked second in yield. So, while air temperature was more strongly correlated than soil temperature to yield, it is possible that the statistical influence of very high air temperatures in the very high-yielding low tunnels masks the importance of soil temperature in this correlation comparison. Even more probable is that the combination of high air and soil temperatures in the low tunnels had a synergistic effect on yield.

Economic Perspective. It is noteworthy that the high tunnel and bare soil plots, which require the greatest and the least initial investment, respectively, produced the most similar yields. Our results suggest high tunnels are not an advisable production system for amaranth. High tunnels could be used to greater effect for amaranth with different ventilation procedures, but tailoring high tunnel temperature controls to amaranth would eliminate the possibility of polyculture with higher-value crops.

The similarity of low tunnel and black plastic plot yields is equally notable. Low tunnel yields were significantly greater than black plastic yields in all but the third

planting, but black plastic yields were still roughly 50% higher than high tunnel yields and 70% higher than bare soil yields on average. Low tunnel materials, though relatively inexpensive, are an additional cost compared to black plastic mulch alone. Crop accessibility can also become an economic consideration for low tunnels. When low tunnel plastic was removed for pesticide control in the second planting, low tunnel air temperature dropped drastically to around only 1°C (1.8°F) greater than the bare soil air temperature the day. The fact that crop access negates, if temporarily, the microclimate effect of the production system is unique to low tunnels and should not be overlooked in economic assessment of the system.

Nonetheless, low tunnel plastic is the only recurring material cost for low tunnels. At around \$150 for 1,000 row-feet, the low tunnel plastic for each planting in this experiment cost under five dollars. The retail cost of amaranth greens, estimated by a collection of seven sources in 2017, was \$2.89/lb (Gary et al., 2017). At the planting density used in this experiment, the cost of low tunnel plastic was justified. For the additional five dollars in low tunnel plastic, the difference in yields between black plastic mulch and low tunnel plots amounted to \$41 in the first planting, \$17 in the second planting, and \$13 in the third planting. For the \$0.15 for each row-foot of low tunnel plastic, yield differences amounted to \$1.47/ft in the first planting, \$0.42/ft in the second planting, and \$0.33/ft in the third planting.

Production Timing. The treatment effect of production system diminished as the season progressed, and it is clear that planting date warrants careful consideration in amaranth production in the northeastern region. Bare soil yields in the second planting exceeded the black plastic and high tunnel yields of the first planting. Black plastic

yields in the second planting exceeded the low tunnel yields of the first planting. Low tunnel yields plateaued in the second planting, and were nearly exactly equal in the third planting. Amaranth is often direct-seeded in warmer climates, but the performance of our bare soil plots suggests that intensive bare soil amaranth production in the northeastern temperate climate is only feasible in the warmest summer months, even with greenhouse-started transplants. Amaranth is fast-growing once established, but it is not a vigorous grower in early development; stand establishment has been identified as an issue in growers' guides (Ebert et al., 2011). Although there was 100% survival of our bare soil plants in the first planting, establishment may have been encouraged by even a minor delay in planting.

Leaf to Stem Ratio. There were significant differences in leaf to stem ratios, but there was no pattern to the effects of production method, nor a correlation with yield. These findings indicate that this measure is largely genetic, and outside the influence of production systems. Enhanced breeding would be the logical course for managing this trait. Current amaranth growers could consider production techniques such as repeated harvest to increase branching, but informed variety selection is likely the most powerful resource available.

Conclusions. Amaranth has wide appeal to ethnic produce buyers and potential as a novel substitute for more common greens. Given its short time to harvest, bare soil amaranth production is possible in the northeastern region. However, our results suggest that use of even minimal plasticulture techniques can provide considerable gains in yield and season extension. As previously stated, there is much room for variation within the systems tested here, and each produces an interaction of effects

not fully quantified by this study. Nonetheless, these results can be used to guide growers in investigation of modifications that may result in promising intermediate options. One such option is the use of black plastic mulch within high tunnels. We do not recommend conforming high tunnel ventilation to amaranth temperature requirements, but the positive response of amaranth to black plastic mulch without crop covering indicates this combination would produce favorable results. Of the systems tested here, black plastic mulch raised beds represent an advantageous intersection of positive yield response, easy crop access, and polyculture potential at low cost to growers. Maximum yield and season extension, however, can be achieved through the use of low tunnels.

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CHAPTER 5

CONCLUSION

Amaranth is a promising alternative crop for growers in the northeastern region; these studies demonstrate the importance of informed variety selection and production protocols. The results of these variety trials support clear variety recommendations, based on the standardized production used in these trials. For reliably high yields throughout a long growing season, ‘Green Pointed Leaf’ and ‘Miriah’ are recommended varieties. These two varieties have high leaf to stem ratios and are likely well suited to single or repeat harvest. However, the varieties tested here encompass a wide range of growth habits and appearances, and further investigation of variety-specific production and marketing strategies is justified. It is likely that targeted production, including a focus on planting density and harvest technique, may increase the desirability of stem-heavy varieties like ‘Green Callaloo’ and low-yielding varieties like ‘White Leaf.’

Similarly, the production systems tested here support a clear choice for maximized amaranth yields but indicate that there is room for variation based on growers’ needs. Low tunnels maximized yields, and the recurring cost of low tunnels was justified, even at our relatively thin planting density. However, black plastic mulch, whether alone or in combination with crop covers, is highly recommended. It is likely that the addition of black plastic mulch to high tunnel amaranth production would be beneficial, but higher value crops are recommended for maximizing high

tunnel value. In comparison to bare soil production, all of these systems provide significant gains in yield; bare soil amaranth production is not recommended. With the addition of even minimal plasticulture techniques, amaranth is a viable crop in the northeastern region, and a favorable option for connecting to the growing ethnic vegetable market.

APPENDICES

Chapter 3

Yield ANOVA Planting Dates 1 - 6					
Source	Degrees of freedom	Sum of squares	Mean square	F value	Pr > F
Variety	9	55.16	6.128	22.209	< 0.0001
Planting date	5	9.84	1.967	7.129	< 0.0001
Variety x planting date	45	39.02	0.867	3.142	< 0.0001
Error	180	49.67	0.276	---	---

All-season Yields	
Variety	Average Yield (kg)
Asia Red	1.985
Red Garnet	1.801
Green Callaloo	2.619
Miriah	3.095
Mchicha	2.786
Green Pointed Leaf	3.048
Red Callaloo	1.825
Southern Red	2.738
Red Stripe Leaf	2.623
White Leaf	1.955

Combined average yields of all varieties in each planting date			
	Average yield (kg)		
Planting date	All varieties	Harvest group 1 ^z	Harvest group 2 ^y
1	2.474	2.705	1.933
2	2.111	2.183	1.943
3	2.247	2.308	2.103
4	2.660	2.696	2.574
5	2.571	2.580	2.500
6	2.624	3.151	2.097

^z ‘Red Garnet,’ ‘Red Callaloo,’ ‘Green Callaloo,’ ‘Miriah,’ ‘Mchicha,’ ‘Red Stripe Leaf,’ ‘Green Pointed Leaf’

^y ‘Asia Red,’ ‘Southern Red,’ ‘White Leaf’

Summaries of each planting date						
Seed date	Group 1 ^z			Group 2 ^y		
	Transplant to harvest days	Cumulative GDD	Harvest day-length	Transplant to harvest days	Cumulative GDD	Harvest day-length
15 May	23	374	15:10	28	476	15:08
28 May	24	431	15:02	31	567	14:54
12 June	25	524	14:41	30	665	14:32
30 June	27	674	13:49	29	737	13:47
14 July	24	599	13:32	27	666	13:24
2 Aug	29	651	12:30	36	771	12:11

^z ‘Red Garnet,’ ‘Red Callaloo,’ ‘Green Callaloo,’ ‘Miriah,’ ‘Mchicha,’ ‘Red Stripe Leaf,’ ‘Green Pointed Leaf’

^y ‘Asia Red,’ ‘Southern Red,’ ‘White Leaf’

Yield Planting date ANOVA for each variety						
Variety	Source	Df	Sum sq	Mean sq	F value	Pr > F
Asia Red	Planting date	5	5.474	1.095	3.204	0.305
	Error	18	6.150	0.342	---	---
Red Garnet	Planting date	5	3.372	0.674	8.589	0.0003
	Error	18	1.413	0.079	---	---
Green Callaloo	Planting date	5	4.118	0.824	4.433	0.0085
	Error	18	3.344	0.186	---	---
Miriah	Planting date	5	7.124	1.429	6.146	0.0017
	Error	18	4.173	0.232	---	---
Mchicha	Planting date	5	5.178	1.036	3.488	0.0222
	Error	18	5.344	0.297	---	---
Green Pointed Leaf	Planting date	5	7.971	1.594	2.579	0.063
	Error	18	11.127	0.618	---	---
Red Callaloo	Planting date	5	2.407	0.481	2.311	0.087
	Error	18	3.750	0.208	---	---
Southern Red	Planting date	5	1.202	0.240	0.637	0.675
	Error	18	6.790	0.377	---	---
Red Stripe Leaf	Planting date	5	10.401	2.080	7.224	0.0007
	Error	18	5.183	0.288	---	---
White Leaf	Planting date	5	1.604	0.321	2.408	0.0772
	Error	18	2.397	0.133	---	---

Rank and significance of variety yields in each planting date						
Yield Ranking	Planting Date					
	1	2	3	4	5	6
1	Green Pointed Leaf a	Southern Red a	Mchicha a	Mchicha a	Mchicha a	Miriah a
2	Miriah a	Miriah a	Southern Red a	Red Stripe Leaf a	Green Pointed Leaf ab	Green Callaloo ab
3	Red Stripe Leaf ab	Green Pointed Leaf a	Miriah a	Southern Red ab	Miriah ab	Mchicha abc
4	Green Callaloo abc	Mchicha a	Green Pointed Leaf a	Miriah ab	Red Stripe Leaf abc	Green Pointed Leaf abc
5	Southern Red b	Green Callaloo a	Red Garnet a	Green Pointed Leaf ab	Southern Red abc	Southern Red abc
6	White Leaf bc	Red Stripe Leaf abc	White Leaf ab	Asia Red abc	Asia Red abc	Red Garnet abc
7	Mchicha bc	Red Callaloo abc	Red Stripe Leaf abc	Green Callaloo abc	Green Callaloo abc	Asia Red abc
8	Asia Red bc	Asia Red abc	Green Callaloo abc	Red Callaloo abc	White Leaf abc	White Leaf abc
9	Red Garnet bc	White Leaf bc	Red Callaloo abc	White Leaf bc	Red Callaloo bc	Red Stripe Leaf bc
10	Red Callaloo bc	Red Garnet c	Asia Red bc	Red Garnet c	Red Garnet c	Red Callaloo c

Leaf-percent of total dry weight ANOVA					
Source	Df	Sum sq	Mean sq	F value	Pr > F
Variety	9	4.042	0.4491	171.247	< 0.0001
Planting date	6	0.403	0.0672	25.634	< 0.0001
Variety x planting date	54	0.442	0.0082	3.124	< 0.0001
Error	210	0.551	0.0026	---	---

Average plant yield plotted against average leaf-percent ($r = -0.363$)

Variety CVs	
Variety	CV
Asia Red	35.81
Red Garnet	25.32
Green Callaloo	21.75
Miriah	22.65
Mchicha	24.65
Green Pointed Leaf	29.90
Red Callaloo	28.34
Southern Red	21.53
Red Stripe	31.38
White Leaf	21.33

Chapter 4

Yield ANOVA First Planting					
Source	Df	Type III Sum sq	Mean sq	F value	Pr > F
Production method	3	37.534	12.511	283.88	<0.0001
Variety	1	0.351	0.351	6.200	0.0285
Production method x Variety	2	0.463	0.154	2.73	0.0905

		Sum Sq			
Error	12	0.679	0.241	---	---
Corrected total	31	39.731	---	---	--

Yield ANOVA Second Planting					
Source	Df	Type III Sum sq	Mean sq	F value	Pr > F
Production method	2	13.293	6.647	26.54	0.0010
Variety	1	0.353	0.353	1.95	0.1962
Production method x Variety	2	0.363	0.182	1.00	0.4044

		Sum sq			
Error	9	1.630	0.181	---	---
Corrected total	23	18.126	---	---	--

Yield ANOVA Third Planting					
Source	Df	Type III Sum sq	Mean sq	F value	Pr > F
Production method	3	6.115	2.038	9.87	0.0033
Variety	1	0.498	0.498	2.07	0.1761
Production method x Variety	3	0.356	0.119	0.49	0.6936

		Sum sq			
Error	12	2.889	0.241	---	---
Corrected total	31	11.976	---	---	--

Leaf-percent of Dry Weight ANOVA First Planting					
Source	Df	Type III Sum sq	Mean Sq	F value	Pr > F
Production method	3	0.0568	0.0189	39.87	< 0.0001
Variety	1	0.0164	0.0164	22.31	0.0005
Production method x Variety	3	0.0114	0.0038	5.17	0.0160

		Sum sq			
Error	12	0.0089	0.0007	---	---
Corrected Total	31	0.1002	---	---	---

Leaf-percent of Dry Weight ANOVA Second Planting					
Source	Df	Type III Sum sq	Mean Sq	F value	Pr > F
Production method	2	0.0677	0.0338	29.32	0.0008
Variety	1	0.0077	0.0077	7.76	0.0212
Production method x Variety	2	0.0069	0.0004	0.44	0.6585

		Sum sq			
Error	9	0.0089	0.0089	---	---
Corrected Total	23	0.1002	---	---	---

Leaf-percent of Dry Weight ANOVA Third Planting					
Source	Df	Type III Sum sq	Mean Sq	F value	Pr > F
Production method	3	0.070	0.0023	1.76	0.2245
Variety	1	0.0083	0.0083	9.11	0.0107
Production method x Variety	3	0.0014	0.0005	0.51	0.6826

		Sum sq			
Error	12	0.0109	0.0009	---	---
Corrected Total	31	0.0430	---	---	---

Average yield plotted against leaf-percent of total dry weight ($r^2 = 0.0038$)

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