ABSTRACT

MACHANOFF, CORDELIA A. Investigation of Plasticulture and Conservation Tillage Systems in Organic Flue-cured Tobacco Production. (Under the direction of Dr. David H Suchoff).

As global demand for flue-cured tobacco has declined in the past several decades, converting production to organic has kept some North Carolina growers in business due to the higher prices received for certified organic leaf. Approximately 64% of the U.S. certified organic flue-cured tobacco crop was grown in North Carolina in 2019, with a farm-gate value of $39 million. However, producing flue-cured tobacco organically introduces management challenges to an already complex system. Organic weed and insect pest management requires an integrated approach to achieve sufficient yield and quality. The aim of this research was to identify potential ways to improve pest management and reduce the impact on soil health of organic flue-cured tobacco production. Two studies were conducted to determine if production systems used in other agronomic crops could be successfully integrated with organic flue-cured tobacco production: plasticulture and conservation tillage.

In the first study, field trials were conducted in three environments to compare four colors of polyethylene mulch with drip irrigation to bare ground production with and without drip irrigation. Data collected include light reflectance, soil temperature, soil nitrogen, plant growth, aphid presence, weed emergence and biomass, leaf chemistry, yield and quality. Tobacco yields were significantly greater in mulched treatments in both locations in 2020, but did not differ from the control in 2019. The different colors of mulches had varying impacts on other aspects of production, all opaque mulches suppressed in-row weed emergence and the highly reflective silver mulch treatments had significantly reduced aphid presence. As the first study to evaluate the use of plasticulture and drip irrigation in flue-cured tobacco production, it provides evidence that more research is warranted to optimize the system for organic flue-cured tobacco.

The second study evaluated the impacts of conventional tillage and conservation tillage on weed emergence and organic flue-cured tobacco production. An overwintered cereal rye (*Secale cereal*) cover crop was either conventionally tilled or terminated via roller-crimper and left in place as a mulch layer prior to transplant of flue-cured tobacco. Data collected included cover crop biomass, weed emergence by species, soil resistance, yield, quality and cured leaf chemistry. In all environments, conservation tillage with cover crop mulch reduced weed density and biomass when compared to conventional treatments. In 2019, cured leaf yield was significantly higher under conservation tillage practices than conventional. In 2020, environmental conditions in both locations resulted in crop loss. The result of these field studies indicate that conservation tillage practices may be an effective weed management strategy, and have the potential to improve yields in an organic production system. However, organic flue-cured tobacco grown under conservation tillage is vulnerable to environmental challenges due to the exclusion of in-season cultivation.

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Investigation of Plasticulture and Conservation Tillage Systems in Organic Flue-cured Tobacco Production

by
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A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Crop Science

Raleigh, North Carolina
2021

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DEDICATION

To my partner in all things, Chris Machanoff. Thank you for always being there, believing in me and supporting my dreams no matter what. I am so grateful for you.

BIOGRAPHY

Cordelia Machanoff was born in Manhattan, New York and lived in Cleveland, Ohio during her early childhood. She then spent her formative years roaming the 365 acres of the Rochester Folk Art Guild on East Hill Farm in rural Upstate New York where she was usually barefoot with her nose in a book. Growing up with farm chores and homegrown food instilled a love for the land and the effort and care it takes to steward it. In her undergraduate years, her interest in food and agriculture grew and she worked on farms across the U.S. and abroad. After graduating from Boston University with a degree in International Relations, she worked as a vegetable CSA farmer, providing food to for 100 families in the Monroe County, NY and the Finger Lakes region. After running variety trials for a local seed company on the farm, her interest in agricultural research led her to join the Cornell Vegetable Program as a field research technician. She became an Extension and research program aide, managed several vegetable production research projects, and found great joy in working collaboratively with growers and researchers to investigate agricultural issues. After spending a year travelling the world with her partner in 2018, she took the opportunity to become Dr. David Suchoff's first graduate student at North Carolina State University in 2019.

ACKNOWLEDGMENTS

Many thanks to my advisor and committee members, Dr. David Suchoff, Dr. Matthew Vann and Dr. Alex Woodley, for your patient and caring guidance over the past two years. You have all played a role in providing the support I needed to have a productive and positive graduate school experience. I also want to thank the staffs of the Cunningham, Upper Coastal Plain and Border Belt Tobacco Research Stations for your role in carrying out this research. Much appreciation to Shannon Henriquez-Inoa, Tom Stanton and Jeremy Machacek for always making sure I had help when I needed it. Deepest gratitude to my fellow students in the Alternative Crops and Organic Production Systems Lab, thank you all for your invaluable help in the field. Finally, thank you to my family and friends who have supported me on this journey. I have received so much from so many, I am filled with gratitude.

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LITERATURE REVIEW ON THE USE OF POLYETHYNE MULCHES, COVER CROP MULCHES AND CONSERVATION TILLAGE IN THE PRODUCTION OF ORGANIC FLUE-CURED TOBACCO (Nicotiana tabacum L.)

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Introduction

Organic agriculture has grown from an obscure response to agricultural industrialization in the mid-20th century to a $55 billion dollar industry (Obach, 2015; Organic Trade Association, 2020). Driven by consumer and grower environmental and health concerns, the production system is now a relatively small but rapidly growing sector of global agriculture. Organic production in the U.S. grew from 14,540 farms on 1.7 million hectares in 2007 to 16,585 on 2.2 million hectares in 2019 (USDA-NASS, 2009, 2020). The farm gate value of organic products increased even more dramatically, from $3.16 billion in 2007 to $9.9 billion in sales in 2019 (USDA-NASS, 2009, 2020). Demand for organic products is especially strong in the European Union (EU) with a $45 billion market and tracked U.S. organic exports to the EU of over $20 million (USDA-FAS, 2020). Growth in demand for U.S. organic products is also strong in East Asian and Middle Eastern countries (Organic Trade Association, 2017).

Organic production has followed an even steeper upward trend in North Carolina. Between 2011 and 2019, the number of USDA certified organic farms increased from 92 on 3,929 hectares to 347 farms on 17,296 hectares (USDA-NASS 2012, 2020). The value of organic crop sales grew from just over $12 million in 2011 to $105 million in 2019. With a 775% increase in revenue from crop sales, it is not surprising that North Carolina growers report plans to increase acreage by more than 3,642 additional certified hectares within the next three years (USDA-NASS, 2020). Out of the state's 3,411,711 hectares of agricultural land, approximately 0.5% is certified organic, indicating that there is ample room to increase organic production according to global demand (USDA-NASS 2017b, 2018).

Among the 347 certified organic North Carolina farms recorded in 2019, 232 included some area of cropland and of those, 119 produced 5.4 million kg of certified organic flue-cured tobacco (*Nicotiana tabacum* L.), approximately 5% of the flue-cured tobacco crop in the state (Vann et al., 2019). With a farm gate value of $39 million, tobacco is the most valuable organic crop grown in North Carolina and second most valuable agricultural commodity after chicken eggs (USDA-NASS, 2017b). With this level of production, North Carolina tobacco growers produce nearly 64% of the total U.S. organic flue-cured tobacco crop (Vann et al., 2019). North Carolina also ranks first in conventional flue-cured tobacco production in the U.S., producing 106 million kg and accounting for 78.7% of total U.S. production in 2019 (USDA-NASS, 2020).

Despite playing a crucial role in the North Carolina economy for over a century, the future of tobacco production is not certain. North Carolina tobacco production peaked in 1939 with 341,000 hectares harvested. The lowest year recorded was 2019 with 47,000 hectares harvested due to decreased domestic demand and international trade issues (USDA-NASS, 2020). Converting some or all tobacco acreage to certified organic has helped many multi-generation families keep farming over the last several decades (Little et al., 2018). Demand constitutes a small percentage of the total tobacco market, but the higher prices received for certified organic flue-cured tobacco can make up some of the lost revenue. While conventional flue-cured tobacco price has hovered under $4.30 per kilogram over the last five years the price for certified organic was $7.21 per kilogram in North Carolina in 2017 (USDA-NASS, 2020; Vann et al., 2019).

Organic Flue-Cured Tobacco Production

Flue-cured tobacco is currently the most widely grown tobacco in the world due to the high sugar content that creates a high quality end product (Peedin, 1999). These sugar levels are due in part by the unique curing process, accidentally discovered in 1839 in Caswell County, NC by an enslaved man named Stephen (North Carolina Department of Cultural Resources, 2008). The process involves precise control of moisture and temperature in specialized facilities resulting in the degradation of chlorophyll and carbohydrate conversion to simple sugars. Production of flue-cured tobacco was developed in the early 19th century on sandy North Carolina soils with limited fertility. Tobacco is well suited to these soil types and the hot and humid growing season typical of the state (Collins & Hawks, 1993). A native plant to North and South America, it is theorized that domestication began 6,000 to 8,000 years ago and cultivation in what is now the southeastern United States began approximately 2,500 years ago (Tushingham, 2018). European colonizers capitalized on the value of tobacco and the suitable climate, utilizing slavery and international trade to support the growth of a robust agricultural economy in which most commercial growers had some land dedicated to the crop (Robert, 1967).

The production of conventional flue-cured tobacco evolved dramatically over the centuries. For most of its history, tobacco production could have been classified as organic by today's standards (Kohrman & Benson, 2011). Now it is a largely mechanized process with improvement in genetics and the use of synthetic chemicals driving increases in yield, quality, and nicotine content (Bowman et al., 1984). Although production is more efficient than ever, demand has declined over the last several decades. U.S. flue-cured tobacco production in 2019 was 134 million kilograms, a 100 year low. This downward trend is unlikely to reverse due to shifting demand and policies (Brown, 2021). In the 1980s, a demand for organically grown tobacco began to emerge, particularly in the southwestern region of the U.S. (Little et al., 2008). Seeking to increase production, the Santa Fe Natural Tobacco Company approached experienced North Carolina, Virginia, and Kentucky growers. Although the "natural," or organic practices they wished to revive were used for most of tobacco growing history, many growers were skeptical of both the management practices required and the potential market demand (Little et al., 2008). However, the growing demand for certified organic flue-cured tobacco gave some southeastern growers the opportunity to continue producing tobacco even as the global conventional market declined.

Challenges in Organic Flue-Cured Tobacco Production

Tobacco producers face many challenges. These range from production issues similar to other high value crops to very specific methods necessary to produce a good yield of high quality tobacco. For example, removal of the apical meristem prior to flowering and close management of fertility to optimize leaf maturity and chemical composition. Producing certified organic tobacco adds layers of obstacles specific to that system, by allowing only materials certified by the Organic Materials Review Institute (OMRI) for use under the USDA National Organic Program (USDA-NOP, 2016). Tobacco growers of the Southeastern U.S. have developed management techniques to produce a quality product within the constraints of certification by reviving older methods and adopting practices from other organic cropping systems. For example, growing sunflowers around organic tobacco fields to attract beneficial predatory insects to manage insect pests and collaborating with university researchers to identify the best combinations of organic fertilizers for tobacco production. (Little, et al. 2008).

Conventional weed management in tobacco uses an integrated approach, maximizing the impact of the seven allowed herbicides by utilizing cultural techniques including deep tillage and cultivation (Gooden et al., 2008; Vann et al., 2021a). Organic flue-cured tobacco production takes this a step further. The lack of effective OMRI listed herbicides makes weed management a major challenge in organic production (Bond & Grundy, 2001). With tillage and cultivation as primary weed management strategies, additional challenges are created. In the short term, cultivation is expensive and can be challenging to time properly. In a wet season, when farmers cannot get equipment into the field, cultivation delays can cause significant yield reduction or crop loss. Tillage in both conventional and organic flue-cured tobacco production is important beyond weed management. Deep tillage, ridge (bed) formation and multiple in-season cultivations are used to reduce soil clodding, promote soil drainage, and reduce constriction of root growth (Britt & Slater, 1957; Bathke et al., 1993; Collins & Hawks, 1993; Flower, 2001; Troeh & Thompson, 2005, Vann et al., 2021a). Over the long term, soil subjected to repeated cultivation may be at risk of degradation due to erosion, compaction, and decreased water holding capacity due to structural breakdown (Claassen et al., 2018).

Like weed management, insect management in flue-cured tobacco requires an integrated approach. The primary insect pests that cause economic damage are green peach aphid (*Myzus persicae* S.), tobacco hornworm (*Manduca sexta* L.), tobacco budworm (*Heliothis virescens* F.), and tobacco thrips (*Frankiella fusca*), which are a vector for tomato spotted wilt virus (Burrack, 2021). Unlike organically approved herbicides, there are many materials labelled for use as organic repellants or insecticides, however there is limited information about their efficacy (Toenisson & Burrack, 2018). OMRI-approved insecticides also tend to be expensive and need to be applied pre-emptively, requiring management before pests become an issue. The choice to apply an insecticidal soap or crop oil that may have low efficacy or a broad spectrum pyrethroid product that harms the entire insect complex presents additional challenges if fruiting crops requiring pollination that are grown on the same farm. Many growers utilize an integrated approach and plant companion crops that attract predators of pests, such as rows of sunflowers meant to attract ladybugs (*Hippodamia convergens, Coccinella septempunctata)* which prey on aphids (Little et al. 2008) .

Yield and quality of flue-cured tobacco depend heavily on the timing and quantity of nutrients. Nitrogen plays a particularly important role in the chemical and physical qualities of the harvested product. Although overall nitrogen requirements are low (approximately 75 kg ha^{-1}) the timing of availability is critical (Collins & Hawks, 1993; McCants & Woltz, 1967). Too little nitrogen and yield will suffer, too much and quality will be reduced (Collins & Hawks 1993). In conventional systems, fertilizers that contain primarily inorganic sources of nitrogen are preferred as they provide the ideal curve of nitrogen availability with most uptake occurring in early growth and a decline at or around topping (removal of blossoming terminus) to allow the leaves to ripen and cure optimally (Weybrew et al., 1983). Organically approved fertility sources are typically very low in mineral nitrogen and require microbial mineralization to release the plant available nitrogen forms (ammonium and nitrate) in the soil and therefore require increased management to optimize timing of nitrogen availability (Collins & Hawks, 1993; Havlin et al., 2013; Vann et al., 2021b). Organic flue-cured tobacco producers typically use a combination of commercially available animal and plant by-products requiring microbial mineralization and sodium nitrate. The latter is immediately plant available, however it is typically limited to 20% of crop need by tobacco contracting companies (Vann et al., 2021b). The release of plant available nitrogen from organic fertility sources is facilitated by microbes and varies with soil temperature, moisture and soil type (Prasad & Power, 1997; Mikkelsen & Hartz, 2008). A risk inherent to the use of organic nitrogen fertility sources is that insufficient soil moisture will delay the mineralization process, causing nitrogen to become plant available with inopportune timing, however recent research found that prolonged N availability from cover crops did not negatively impact yield or quality (Vann et al., 2019; Hahn et al., 2021).

As organic tobacco increases its share of North Carolina tobacco production, looking for solutions from other cropping systems may provide growers with strategies to address persistent challenges while increasing overall sustainability. Two potential alternative cropping systems that have gained popularity in similar crops involve utilizing mulches: plasticulture and conservation tillage. Plasticulture utilizes polyethylene mulches and drip irrigation and is widely used in other high value crops due to the many impacts on soil, pest, and weed management and crop growth. This system-neutral cropping strategy is suitable for both conventional and organic production and may offer solutions to the specific challenges faced by organic flue-cured tobacco growers. Conservation tillage is another potential option for organic flue-cured tobacco producers, which minimizes soil disturbance by planting the cash crop directly into biomass residues of an overwintered cover crop using specialized planting equipment. Utilizing conservation tillage and cover crop mulches may offer additional benefits such as improved soil health (e.g. increased rainwater infiltration, water-holding capacity, reduced erosion), reduced production costs such as fuel and labor, reduction in sediment, nutrient, and pesticide runoff while providing a barrier to weed emergence (Rawls et al., 2003; Moebius-Clune et al., 2008; Claassen et al., 2018). The existing research on alternative tillage practices in tobacco offers mixed results that depend heavily on soil and weather conditions.

Polyethylene Mulch uses, benefits and barriers to adoption

Polyethylene mulches are used on over 8,000,000 hectares worldwide in small fruit and vegetable production to manage in-row weed populations, buffer soil temperatures, limit rain-induced soil loss, and maintain soil moisture (Briassoulis & Giannooulis, 2018; Kasirajan & Ngouajio, 2012). In addition, mulches may impact chemical and biological properties of the soil (Bhardwaj & Kendra, 2013). Beginning in the 1950s, plastic mulches were used with the aim of increasing soil temperatures to promote germination. Over 70 years of research has resulted in a body of knowledge regarding the many variables impacted by this production system in a wide variety of crops (Kasirajan & Ngouajio, 2012).

Generally referred to as plasticulture, polyethylene mulches are used in a system in which the mulches cover the top and sides of raised beds, a line of drip tape provides precision irrigation and fertilization, and the crop is planted in holes at the appropriate spacing in the mulch. This system is used in high value crops because specialized equipment is required and the mulches and drip irrigation add additional production cost, approximately $400-625 ha^{-1} or more per season (Kasirajan & Ngouajio, 2012). Crops commonly grown on polyethylene mulches in the U.S. include bell pepper (*Capsicum annuum*), muskmelon (*Cucumis melo*), eggplant (*Solanum melongena*), slicing cucumber (*Cucumis sativus*), summer squash (*Cucurbita pepo*), tomato (*Solanum lycopersicum*), and watermelon (*Citrullus lanatus*; Ngouajio et al., 2008). Plasticulture was adopted in North Carolina in the 1980s in strawberry production and has become widely used in fresh market vegetable production (Poling 1993; Sanders 2001).

Numerous studies have shown that many crops grown on polyethylene mulches have consistently higher yields than those in bare ground production (Schonbeck & Evanylo, 1998; Farias-Larios & Orozco-Santos, 1997; Ibarra-Jiménez et al., 2008). There are a number of variables impacted by the plasticulture system that may account for these yield differences (Kasirajan & Ngouajio, 2012). Different mulch colors and materials reflect different amounts of light, which can have a variety of impacts on both crop canopy and soil conditions during the growing season (Decoteau, et al., 1988; Ballare et al., 1995; Lee et al., 1996). Black and clear mulches raise soil temperature, while white and reflective mulches create cool soil conditions due to the increased light reflectance (Ham et al., 1993; Lamont, 2017).

Mulch color can have a significant impact on insect pest populations. Highly reflective mulches may impact insect pressure in the crop canopy due to the use of visual cues, and attraction or repulsion to high or low UV reflectance (Matteson, et al., 1992; Csizinszky et al., 1995). Silverleaf whitefly (*Bemisia argentifolii* Bellows & Perring) was repelled in pumpkin (*Cucurbita maxima*), cucumber (*Cucumis sativus*) and zucchini (*Cucurbita pepo*) crops leading to populations equivalent to crops treated with imidacloprid (Summers & Stapleton, 2002). Several studies have also demonstrated attraction and repulsion of aphid species by different colors of plastic mulches where highly reflective silver mulch resulted in the lowest aphid populations and therefore least incidence of aphid vectored viral diseases in fruiting crops (Jones 1991; Brown et al., 1993; Webb et al., 1994; Canul-Tun et al., 2017).

Red mulch reflects greater light in the red and far-red wavelengths, and has been shown to increase leaf area and secondary metabolite production in lettuce and strawberries (Loughrin & Kasperbauer, 2001; Franquera, 2011) In studies of fruiting crops including cucumber and bell pepper, red mulch produced higher leaf biomass, which is undesirable when the leaves are not marketable but may be beneficial in tobacco where increased leaf area translates into increased yield (Decoteau, 2008; Torres-Olivar et al., 2016). Leaf chemical composition is important in tobacco production because the levels of alkaloids, reducing sugars and nitrates impacts the final quality and value of the crop. Environmental factors can impact these levels, for example root zone temperature has been shown to have a greater effect on nitrate concentration in tobacco leaves than aerial temperature or soil NO_3- concentration (Osmond & Raper, 1981). Polyethylene mulches may beneficially impact leaf chemical composition by either altering light wavelength reflectance in the canopy or soil temperature.

Weed management is among the most frequently cited benefits of using polyethylene mulches (Price & Norsworthy, 2013). In conventional systems, mulches may reduce herbicide use and can be a component of an integrated weed management system (Chalker-Scott, 2007). In organic systems where herbicide use is not an option, mulches are even more widely used for weed suppression, due to the lack of effective OMRI-approved herbicides and challenges presented by mechanical and other cultural management practices (Bond & Grundy, 2001). Mulching also eases the need for repeated mechanical control during the growing season.

A large body of research exists on the impacts of polyethylene mulches on crop yield and quality from many different angles, but relatively little work exists on their impact on plant available soil nitrogen levels. Polyethylene mulches buffer soil temperatures and alter soil moisture status (Kasirajan & Ngouajio, 2012). These variables have been shown to impact the rate of microbial nitrogen mineralization (Gale, 2006). Studies conducted to determine the relationship between root zone temperature and crop yield in cucumber, potato, tomato, squash, bell pepper, and watermelon using different colors of mulch to obtain different root zone temperatures, and increased root zone temperature is one of the most often cited benefits associated with plastic mulches (Brown et. al., 1996; Farias-Larios & Orozco-Santos 1997; Schonbeck & Evanylo 1998; Ibarra-Jiménez et al., 2008; Diaz-Pérez 2009; Ibarra-Jiménez et al., 2011; Canul-Tun et al., 2017; Lamont, 2017). However, the connection between mulch color, soil temperature, and nitrogen mineralization is not well studied. Several studies found that plastic mulch color impacted water and nitrate distribution as well as soil temperature and crop yield, however the research focused on potential NO_3-N leaching to groundwater (Filipovic et al., 2016; Chen, 2020).

Altering the edaphic environment by using a different type or color of mulch may alter the amount of plant available nitrogen over the growing period due to differences in soil temperature or moisture levels that in turn impact microbially-driven nitrogen mineralization (Havlin, 2013). Organic growers rely on nitrogen fertilizers from plant and animal sources, primarily manures, cover crops, composts, feather and blood meal, and alfalfa and soybean meal. The majority of nitrogen in these fertility sources is in forms not immediately available to plants and require soil microbes to mineralize the nitrogen to plant available nitrogen (PAN), either ammonium (NH_4^+) or nitrate (NO_3^-) (Mikkelsen & Hartz, 2008; Havlin et al., 2013). This microbially-driven mineralization process is moisture and temperature dependent, making it difficult for growers to synchronize nutrient release with plant demand. Understanding the impact of different mulch types on nitrogen mineralization will help determine the proper quantity and timing of fertilizer application to meet crop demands.

Criticism of the system is focused on the post-harvest fate of mulching materials. Worldwide, approximately 1.0 mt of plastic mulch is disposed of in landfills each season (Briassoulis & Giannooulis, 2018). Biodegradable options are available and used in conventional systems, but have not been approved for certified organic use in the U.S. due to the persistence of photodegraded materials in soils (Goldberger et al., 2015; Miles et al., 2017). Other barriers to adoption include the start-up costs of installation equipment and the additional cost of materials, which can be difficult to balance in crops with already tight profit margins.

Mulches are not typically used in tobacco production because of the reliance on repeated tillage for hilling around the base of the plants in both conventional and organic production

(Vann et al., 2021a). There are concerns that without the repeated tillage and deposition of soil around the plant base, high winds could cause lodging and interfere with growth and harvest. Integration of black plastic polyethylene mulch and drip irrigation was shown to increase yields and decreases tobacco specific nitrosamine concentrations in burley tobacco (Caldwell et al., 2010). There is no published information regarding the suitability or impacts of plasticulture in flue-cured tobacco production systems. Adapting the tobacco production system to incorporate mulches could reduce soil disturbance and prevent weeds in wet periods when tillage is not feasible, in addition to the other variables impacted by polyethylene mulches. With mulch characteristics that may improve weed, insect pest and nutrient management, plasticulture may be a possible natural fit for organic flue-cured tobacco production. Organic flue-cured tobacco is often grown in rotation with other high-value, intensively managed crops that are well suited to the plasticulture system. Although tobacco yields depend on high biomass production and fruiting crops are most widely grown with plastic mulches, tobacco belongs to the same family as tomato and pepper, two Solanaceous crops particularly well suited to plasticulture production (Caldwell et al. 2010).

Conservation tillage in organic systems

Conservation tillage has been a component of sustainable agriculture in the United States since the mid-20th century. Defined as any tillage system that leaves a minimum of 30% of residue from the preceding crop after planting of the subsequent crop with the aim of reducing soil erosion by water, conservation tillage is a sub-category of reduced tillage in general (Conservation Technology Information Center, 2002). The devastation of the Dust Bowl in the 1930s sparked interest in reducing tillage for environmental reasons, but did not become widely adopted until the development of herbicides in the 1960s, which reduced grower reliance on tillage for weed management (Faulkner, 1943; Franklin & Bergtold, 2020). In 2017, an estimated 72% of U.S. acreage for which a tillage system was reported were managed with either no-till or conservation tillage, nearly 81 million hectares in total (USDA, 2019). Implementation of conservation tillage offers numerous on- and off-farm benefits including a general improvement in soil health (e.g. increased rainwater infiltration, water-holding capacity, reduced erosion), reduced production costs such as fuel and labor, improved weed management, and reduction in sediment, nutrient, and pesticide runoff (Uri et. al., 1998; Rawls et al., 2003; Stavi et al., 2011; Moebius-Clune et al., 2008; Wezel et al., 2014; Claassen et al., 2018). Despite the widespread implementation of conservation tillage, rates of adoption vary widely among specific crops and agricultural regions and the Southeastern U.S. has among the lowest rates of conservation tillage and no-till production (Claassen et al., 2018).

One common method of implementing conservation tillage involves minimizing soil disturbance by planting the cash crop directly into biomass residue of an overwintered cover crop, although high residue crops like corn are often followed with another cash crop without a cover crop in between (Clark & SARE, 2007; Bergtold et al., 2020). Cover crops offer benefits including prevention of soil erosion, nitrate leaching, soil compaction, and increased soil organic matter, water infiltration and weed control (Dabney, 2001). In conventional production, the cover crop residue is used in conjunction with herbicides for weed management (Price & Kelton, 2020).

Conservation tillage has been less widely adopted in organic production, but is of interest to researchers and growers for soil health maintenance. Conservation tillage is the practice of reducing tillage such that the Soil Tillage Intensity Rating (STIR) is less than or equal to 80 and does not use a moldboard plow, including mulch-till, no-till or strip till (Claassen et al., 2018). Organic growers face the challenge of managing weeds and terminating cover crops without effective and affordable OMRI listed herbicides (Peigne et al., 2007; Teasdale et al., 2007; McErlich & Boydston, 2014; Armengot et al., 2015). Weeds and cover crops must be managed with systems-based approaches that typically involve mechanical operations such as mowing, rolling, under-cutting, and various tillage operations ranging from deep tillage to shallow cultivation (Bond & Grundy, 2001; Creamer & Dabney, 2002). Weed management is often cited as the most pressing challenge in organic agriculture (Bond & Grundy, 2001; Bàrberi, 2002; McErlich & Boydston, 2014). In areas with high weed pressure or populations of perennial weeds, organic conservation tillage may not be practical and can lead to increased weed issues (Teasdale et al., 2007).

The level of weed control provided by rolled cover crop mulch varies widely depending primarily on the weed species present in a given location and the amount of cover crop biomass (Mirsky et al., 2013). Several studies have shown that a high biomass cover crop mulch used in conjunction with conservation tillage can be successfully utilized in organic systems provided that the cover crop biomass is sufficient to prevent weed emergence (Smith et al., 2011; Mirskey et al., 2013; Reberg-Horton et al., 2013). The cover crop biomass target is important to note, the mulch layer must be sufficient to exclude light and avoid triggering weed seed germination and not decompose during the critical period of weed control for the specific crop (Teasdale & Mohler, 2000; Blanco-Canqui et al., 2015). Cover crop species selection is also crucial in organic conservation tillage systems. The cover crop species must be able to be terminated at the correct timing via rolling or mowing and have sufficiently high carbon to nitrogen ratio to prevent rapid decomposition (Madden et al., 2004).

Davis et al. (2010) and Smith et al. (2011) reported that cover crop biomass of greater than 8,967 kg ha^{-1} is necessary to sufficiently suppress weed emergence in soybean in Illinois and North Carolina, while Mirsky et al. (2013) identifies a threshold of 8,000 kg ha^{-1} cereal rye biomass residue for consistent suppression of annual weeds. Publications by Sustainable Agriculture Research and Education (SARE) claim that rolled cereal rye mulch biomass as low as 6,725 kg ha^{-1} can provide sufficient control (Schonbeck & Morse, 2020). A study in reduced tillage vegetables in Maryland found that a winter cover crop reduced weed emergence the following growing season by 50% and greater cover crop biomass residue is correlated with reduced weed density, with either positive or no impact on crop yield. Studies in cotton and soybean reported weed density reduction of 26, 54, and 56% despite relatively low biomass production of 6,250 and 2,840 kg ha^{-1} in the former two cases up to 8,000 kg ha^{-1} in the latter (Reeves et al., 2005; Davis, 2010; Buchanan et al., 2016). In order to achieve the estimated necessary period of weed control for flue-cured tobacco, a sufficiently thick layer of cover crop mulch is required to prevent weed emergence between two and 6.5 weeks after transplant (Inman et al., 2018).

Despite adoption of conservation tillage practices in tobacco-growing regions, tobacco growers have been slow to adopt practices that reduce tillage (Fisher, 2004; Pearce & Denton, 2013). Both conventional and organic flue-cured tobacco production rely heavily on repeated tillage, for field preparation, raised bed formation and multiple post-transplant cultivation operations for weed management, soil drainage and decreased mechanical impedance of root growth (Britt & Slater, 1957; Vepraskas & Miner, 1986; Collins & Hawks, 1993; Gooden et al., 2008, Van et al., 2021a). These practices result in between 33 and 40 tons ha^{-1} average annual soil loss (Wood & Worsham, 1986). Although the main benefits of reducing tillage are related to soil health, there are other advantages of reducing tillage specific to tobacco production: the cover crop mulch retains soil moisture, prevents soil splashing on lower leaves, and fewer cultivations translates into saved time and money (Pearce & Denton, 2013).

Field evaluation of cover cropping and conservation tillage systems in tobacco production have mixed results in terms of tobacco yield and quality and overall positive results in terms of soil health, with conclusions calling for additional research in a potentially feasible system (Britt & Slater, 1957; Hoyt, 1986; Wood & Worsham, 1986; Bathke et al., 1993; Collins & Hawks, 1993; Fisher, 2004; Gooden et al., 2008). Research in burley tobacco showed that no tillage and conservation tillage compared favorably to conventional tillage on a deep, well drained loam soil, but yielded significantly less on a well-drained silt loam soil with fragipan (Pearce and Denton, 2013). Hoyt (2000) reported equivalent yields and nitrate levels in burley tobacco produced under conservation tillage and cultivation (conventional tillage) in Western North Carolina, having found higher tobacco yields were associated with thick residue accumulation in an earlier North Carolina strip tillage study (Hoyt, 1986). Wood and Worsham (1986) reported between 20 and 90 times greater soil loss with conventional tillage over no tillage depending on the soil type in North Carolina's coastal plain tobacco growing region, and Hazel (2008) documented an 82% reduction in sediment loss in tobacco fields with reduced tillage. Zou et al. (2015) report that reduced- and no-tillage production increased soil aggregation and soil organic carbon and total soil nitrogen compared with conventional tillage production but did not produce a yield benefit even in a dry season due to low tobacco root density resulting from higher penetration resistance in the no-tillage treatment (Zou et al., 2017).

Poor weed control, potential for lodging, and restricted root growth have been cited as the primary barriers to adoption of reduced tillage in flue-cured tobacco, likely due to differences in the soil characteristics of the different regions where burley and flue-cured tobacco are grown (Fisher, 2004). Flower (2001) reported significantly decreased yield and quality in conservation tillage compared with conventional tillage in flue-cured tobacco in Zimbabwe in the first two years of study, attributed to restricted root growth and nitrogen leaching. In a follow up study where additional nitrogen was applied and a ripper tine was used within the row in the conservation tillage treatment, there were no yield differences between conservation and conventional tillage. Wood and Worsham (1986) observed significantly decreased soil loss alongside a 13% yield reduction in no-till flue-cured tobacco on Bibb soils, but equivalent yields on Goldsboro soils prone to moisture loss, suggesting that the rye cover crop mulch preserved yield in a dry year. Gooden et al. (2008) identified other challenges with reducing cultivation in flue-cured tobacco including increased problematic suckers, increased lodging, and decreased yields in a study focused on reducing tillage via strip-tillage. Despite the continued soil degradation caused by flue-cured tobacco production, research has supported the continued use of conventional tillage due to the complexity of the production system and vulnerability to unfavorable growing conditions.

It is documented that raised ridged or bedded production support good drainage and prevent water accumulation in the root zone, to which flue-cured tobacco plants are particularly sensitive (Britt & Slater, 1957; Collins & Hawks, 1993). Flat ground production may leave the tobacco crop vulnerable in periods of excessive rainfall and the risk of lodging and sucker production also increase. Research where a high-biomass winter cover crop mulch is utilized to prevent weed emergence in the subsequent season is generally conducted on flat ground in crops that are typically grown without ridged rows or raised beds and it is unknown whether the two systems could be combined to accommodate the growing practices used to produce flue-cured tobacco. It may also be possible to achieve acceptable tobacco yields on flat ground if other conditions are met. Bathke et al. (1993) found ridged or level ground production had no impact on yield in flue-cured tobacco yield.

Conclusion

Organic flue-cured tobacco is an important part of the Southeastern agricultural economy and grows in importance to North Carolina farmers as the future of the global tobacco market becomes more uncertain. Development of research supported recommendations for integration of organic flue-cured tobacco production with alternative growing practices utilizing either polyethylene or cover crop mulches would support growers in simplifying management of all rotational crops and maximize use of specialty equipment. The objectives of the plasticulture study conducted in 2019 and 2020 were to evaluate the potential use of plasticulture in organic flue-cured tobacco, to compare the impacts of different colors of polyethylene mulches on the primary challenges in the organic flue-cured tobacco production system including insect pest, weed and nutrient management. The objectives of the conservation tillage and cover crop study conducted in 2019 and 2020 were to test the hypothesis that a winter cover crop with conventional tillage would reduce weed emergence in organic flue-cured tobacco and evaluate the impact of the alternative tillage system on tobacco yield and quality.

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CHAPTER TWO

EVALUATION OF THE USE OF POLYETHYLENE MULCHES IN THE PRODUCTION OF ORGANIC FLUE-CURED TOBACCO (*Nicotiana tabacum* L.)

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ABSTRACT

Management of weed and insect pests in organic production of flue-cured tobacco is challenging due to lack of effective and affordable approved control options. Polyethylene plastic mulches are commonly used in vegetable and berry production to manage in-row weed populations, buffer soil temperatures, limit rain-induced soil loss, and maintain soil moisture. Mulch color has been shown to impact plant growth, soil temperature and insect pest populations in vegetable crops.

Field trials were conducted at the Cunningham Research Station in Kinston, NC in 2019 and 2020 and at the Border Belt Tobacco Research Station in Whiteville, NC in 2020. Four colors of polyethylene mulch (red, white, black, and silver) with drip irrigation were compared with bare ground with and without drip irrigation. Light reflectance, soil temperature, soil nitrogen, plant growth, aphid presence, weed emergence and biomass, leaf chemistry, yield and quality data were collected.

Tobacco yields were significantly greater in mulched treatments in both locations in 2020, but did not differ from the control in 2019. The different colors of mulches had varying impacts on other aspects of production, all opaque mulches were successful in suppressing in-row weed emergence and there were significantly fewer aphids present in treatments with highly reflective silver mulch. This study is the first to evaluate the use of plasticulture and drip irrigation in flue-cured tobacco production, and although the results were variable, it provides evidence that more research is warranted to optimize the plasticulture system for organic flue-cured tobacco.

INTRODUCTION

Flue-cured tobacco (*Nicotiana tabacum* L.) is an increasingly important organic crop in North Carolina. Among the 347 certified organic North Carolina farms in 2019, 119 produced 5.4 million kg of certified organic flue-cured tobacco, with a farm gate value of $39 million (USDA-NASS, 2017). Though organic flue-cured tobacco amounted to just 5% of the total flue-cured tobacco crop in the state, it represented 64% of the total U.S. organic flue-cured crop produced (Vann et al., 2019).

Despite playing a crucial role in the North Carolina economy for over a century, the future of tobacco is uncertain. North Carolina tobacco production peaked in 1939 with 341,000 hectares harvested. The lowest year recorded was 2019 with 47,000 hectares harvested due to decreased domestic demand and international trade issues (USDA-NASS & NCDACS, 2020). Converting conventional tobacco land to certified organic has helped many multi-generation families keep farming over the last several decades (Little et al., 2018). Demand constitutes a small percentage of the tobacco market, but higher prices received for certified organic flue-cured tobacco can make up some of the lost revenue. While conventional flue-cured tobacco price has hovered under $4.30 per kilogram over the last five years the price for certified organic was $7.21 per kilogram in North Carolina in 2017 (USDA-NASS, 2020; Vann et al., 2019).

Producing certified organic tobacco adds layers of challenges specific to an already complex production system by allowing only materials certified by the Organic Materials Review Institute (OMRI) for use under the USDA National Organic Program (USDA-NOP, 2016). Pest and nutrient management require an integrated approach. With no effective approved herbicides, tillage and cultivation are the primary weed management tools. In the short term, cultivation is expensive and timing can be challenging. Over the long term, soil cultivated repeatedly may be at risk of degradation caused by erosion, compaction, and decreased water holding capacity due to structural breakdown (Claassen et al., 2018).

Unlike herbicides, there are many materials labelled for use as organic repellants or insecticides but the efficacy of these products is unclear (Toenisson & Burrack, 2018). The primary insect pests that cause economic damage in flue-cured tobacco are green peach aphid (*Myzus persicae* S.), tobacco hornworm (*Manduca sexta* L.), tobacco budworm (*Heliothis virescens* F.), and tobacco thrips (*Frankiella fusca*; Burrack, 2021). Without taking a preemptive, integrated approach to managing these insect pests, leaf quality and yield can be dramatically reduced. Organic flue-cure tobacco growers must utilize field selection, crop rotation, and timely sucker removal and topping in addition to OMRI-approved insecticides to minimize pest damage (Vann et al., 2019).

As with insect and weed management, organic fertility is different from conventional management and must be managed properly to ensure optimum yield and quality. Nitrogen plays a crucial role in the chemical and physical qualities of the harvested product and, though overall requirements are low (approximately 75 kg ha^{-1}), the timing of availability is critical (Collins & Hawks, 1993; McCants & Woltz, 1967). Too little nitrogen and yield will suffer, too much and quality will be reduced (Collins & Hawks, 1993). In conventional systems, fertilizers that contain primarily mineral sources of nitrogen are preferred as they provide the ideal curve of nitrogen availability with most uptake occurring in early growth and a decline at or around topping (removal of blossoming terminus) to allow the leaves to ripen and cure optimally (Weybrew et al., 1983). Organically approved fertility sources are typically low in mineral nitrogen and require microbial mineralization to release the plant available nitrogen forms (ammonium and nitrate) and therefore require increased management to optimize timing of nitrogen availability

(Collins & Hawks, 1993; Havlin et al., 2013; Vann et al., 2019). Organic flue-cured tobacco producers typically use a combination of sodium nitrate and commercially available animal and plant by-products requiring microbial mineralization. The former is immediately plant available, however it is typically limited to 20% of overall crop need by tobacco contracting companies (Vann et al., 2021). The release of plant available nitrogen from organic fertility sources is facilitated by microbes and varies with soil temperature, moisture, and soil type (Prasad & Power, 1997; Mikkelsen & Hartz, 2008). A risk inherent to the use of organic nitrogen fertility sources is that insufficient soil moisture will delay the mineralization process, causing nitrogen to become plant available at inopportune times (Vann et al., 2019).

Though not researched in flue-cured tobacco production, plasticulture (the use of polyethylene mulch and drip irrigation) is widely used in fresh market vegetable production (Poling, 1993; Sanders, 2001). Plasticulture has numerous agronomic benefits, including in-row weed management, soil temperature buffering, limiting rain-induced soil loss, and maintaining soil moisture (Kasirajan & Ngouajio, 2012; Briassoulis & Giannooulis, 2018). These benefits can allow for yields between 150% and 500% higher than those in bare ground production (Schonbeck & Evanylo, 1993; Farias-Larios & Orozco-Santos, 1997; Sanders, 2001; Ibarra-Jiménez et al., 2008). Plastic mulches come in a variety of colors including black, white, reflective, red, and clear. Black plastic is often used to increase soil subsurface temperatures whereas white and silver or reflective mulches can keep soils cooler (Decoteau, 2008).

Mulch color can also affect insect pest populations and crop quality. Highly reflective mulches impact insect pressure in the crop canopy due to visual cues and attraction or repulsion to high or low UV reflectance, which can result in lower aphid and thrips populations (Matteson, et al., 1992; Csizinszky et al., 1995).

Red mulch reflects greater light in the red and far-red portion of the visible spectrum, and has been shown to increase leaf area and secondary metabolite production in lettuce and strawberries (Loughrin & Kasperbauer, 2001; Franquera, 2011) In studies of the fruiting crops cucumber (*Cucumis sativus*), tomato (*Solanum lycopersicum*) and bell pepper (*Capsicum annuum*), red and black mulch produced higher leaf biomass, which may be beneficial in tobacco where increased leaf area translates into higher yields (Decoteau, 2008; Torres-Olivar et al., 2016). Leaf chemical composition is important in tobacco production. The levels of alkaloids, reducing sugars, and nitrates impact the quality and value of the crop and environmental factors can impact these level. For example, root zone temperature has been shown to have a greater effect on nitrate concentration in tobacco leaves than soil nitrate concentration (Osmond & Raper, 1981).

Increased root zone temperature is one of the most often cited benefits associated with plastic mulches and numerous studies have documented a relationship between root zone temperature and crop yield in cucumber, potato (*Solanum tuberosum)*, tomato, squash (*Cucurbita pepo*), bell pepper, and watermelon (*Citrullus lanatus*) using different colored mulches (Brown et al., 1996; Farias-Larios & Orozco-Santos, 1997; Schonbeck & Evanylo, 1998; Ibarra-Jiménez et al., 2008; Diaz-Pérez, 2009; Ibarra-Jiménez et al., 2011; Canul-Tun et al., 2017; Lamont, 2017). However, the connection between mulch color, soil temperature, and nitrogen mineralization is not well studied. Several studies found that plastic mulch color impacted water and nitrate (NO_3^-) distribution as well as soil temperature and crop yield, however the research focused on potential NO_3-N leaching to groundwater (Filipovic et al., 2016; Chen, 2020). Altering the edaphic environment by using a different mulch colors may alter the amount of plant available nitrogen due to differences in soil temperature or moisture levels that impact microbially-driven nitrogen mineralization (Havlin et al., 2013). Understanding the impact of different mulch types on nitrogen mineralization will help determine the proper quantity and timing of fertilizer application to meet crop demands.

Research is lacking in the use of plasticulture in flue-cured tobacco. Black plastic mulch and drip irrigation was shown to increase yields and decreases tobacco specific nitrosamine concentrations in burley tobacco (Caldwell et al., 2010). There is no published information regarding the suitability or impacts of plasticulture in flue-cured tobacco production. Adapting the tobacco production system to incorporate mulches could reduce soil disturbance and prevent weeds in wet periods when tillage is not feasible, in addition to the other variables impacted by polyethylene mulches. With mulch characteristics that may improve weed, insect pest and nutrient management, plasticulture may be a possible natural fit for organic flue-cured tobacco production.

The objectives of this study were to 1) compare the impacts of different colored polyethylene mulch on weed and aphid pest populations in organic-flue cured tobacco; 2) determine if polyethylene mulch color affected organic fertilizer nitrogen mineralization rates and; 3) evaluate polyethylene mulch in general as well as mulch color effects on organic flue-cured tobacco yield and quality.

MATERIALS AND METHODS

Site and Experimental Design

Field experiments were conducted at the Cunningham Research Station (CRS) in Kinston, North Carolina in 2019 and 2020 on a Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults), and at the Border Belt Tobacco Research Station (BBTRS) in

Whiteville, North Carolina in 2020 on a Norfolk loamy fine sand (fine-loamy, kaolinitic, thermic Typic Kandiudults). Organic production practices were followed according to the U.S. Federal standards established by the National Organic Program with the exception of CRS in 2020, where imidacloprid treated transplants were used due to the unavailability of untreated plants (USDA, NOP, 2016).

The experiments were conducted using a randomized complete block design with four blocks in both years at CRS and three blocks in 2020 at BBTRS. Six treatments were evaluated: four colors of 1 mm polyethylene mulch film (black, white, red and silver; Berry Hill Irrigation, Buffalo Junction, VA) with 8 mm 0.76 L h^{-1} drip irrigation tape with 30.5 cm emitter spacing (Streamline Plus; Netafim, Fresno, CA) and bare ground with drip irrigation and without drip irrigation. Plots consisted of a single 15 m long row with two bare ground buffer rows on either side spaced at 1.5 m between rows. Buffer rows were used to minimize any light reflectance or absorbance from neighboring treatments. Each plot was extended six additional meters in length to accommodate additional soil sampling conducted at CRS and BBTRS in 2020.

Field Preparation, Fertility Sources and Trial Management

Fields were prepared according to research station management standards including pre-bedding primary and secondary tillage. All fields received a pre-bedding broadcast application of poultry feather meal (NatureSafe 13-0-0, Griffin Industries, Cold Spring, KY) at a rate of 80 kg N ha^{-1} and sulfate of potash magnesia (K-MAG 0-0-22, Helena Agri-Enterprises, LLC, Colliersville, TN) at a rate of 150 kg K_2O ha^{-1}. Raised beds were formed in all plots and drip tape and polyethylene mulches were installed in the same pass in those treatment plots as required. A

3.8 cm lay flat header across the front of the entire trial area provided irrigation from the station hydrant to drip lines.

Station standard tobacco cultivar NC 196 (Goldleaf Seed Company, Hartsville, SC) was transplanted at 60 cm in-row spacing by hand at CRS and by water wheel transplanter at BBTRS on 2 May 2019 and 29 April 2020 in CRS and on 12 May 2020 at BBTRS. All treatments with drip irrigation received approximately 2.5 cm of water per week with no additional overhead irrigation applied. Dead or broken plants were replaced with transplants of the same age one week post-transplant in all environments. No herbicide or cultivation weed management operations were performed in any treatment.

Sample and data collection

Average photosynthetically active radiation (PAR) reflectance and spectral distribution of light reflected by the four mulch colors and bare soil were measured in the field immediately after trial installation at CRS in 2019 using a handheld spectroradiometer (PSM-2500, Spectral Evolution, Lawrence, MA). The spectral range of the sensor is 200 to 2,500 nm with spectral resolution of 3.5 nm at 700 nm, 22 nm at 1,600 nm and 22 nm at 2,100 nm with the percent reflectance output in 1 nm increments. Measurements were taken at solar noon on a cloudless day 61 cm above the mulch or soil surfaces. Average PAR reflectance was calculated by averaging reflectance values across the PAR spectrum (400 nm $\geq \lambda \geq$ 800 nm) for each treatment replicate.

Soil temperature at 10 cm depth was measured hourly from trial establishment through harvest using wireless soil temperature data loggers (Tidbit MX Temperature 400’, Onset

Computer Corporation, USA). Data loggers were buried in approximately the center of each treatment plot, with mulch replaced over the soil surface in mulched treatments.

Plant growth was measured every 7 d from one week post-transplant through topping. Ten center plants per plot were measured from the soil surface to the base of the apical meristem. The same ten plants per plot were measured except in cases of occasional mortality.

Adult green peach aphids (*Myzus persicae*) were counted on the same plants used to measure plant growth. In CRS 2020 where treated plants were used due to unavailability of untreated plants, aphid bodies were counted and removed from the plants after counting. In the other two environments, live or dead aphids were counted and left on the plants.

In-row weed emergence count and biomass data were collected approximately one month post-transplant. Weeds within one random 30.5 cm by 30.5 cm square per plot were cut at the soil line, counted and dried at 65°C for 72 h prior to weighing. Monocot, dicot and *Amaranthaceae* spp. were counted and weighed separately.

Leaf tissue chemical concentrations were evaluated midseason at topping with green leaves and at harvest on composite cured leaf tissue. Topping date was determined by visual assessment of more than 50% of treatment plants in blossom just prior to scheduled flower removal, approximately 8-10 weeks post-transplant. Green leaf samples were collected by removing the most recently fully expanded leaf, generally the fourth leaf down from the apical growing tip, from five randomly selected plants within the treatment row. Typical sampled leaf size was approximately 10 cm by 15 cm. Composite cured leaf samples were selected post-curing from a homogenized sample of tissue from all stalk positions and harvest dates. Leaf samples were ground to <80-mesh after drying at 65°C for 72 hours. Leaf tissue chemical analysis was conducted by NCSU Tobacco Analytical Services lab. Total leaf NO_3^- concentration was analyzed using Macro-Kjeldahl method described by Nelson and Sommers (1973) and total alkaloid and reducing sugars were analyzed with a Perkin-Elmer Autosystem XL Gas Chromatograph system using the methods described by Davis (1976).

Soil samples were collected at transplant and 1, 3, 7 d after transplant followed by weekly sampling for 8 weeks at BBTRS 2020 and 9 weeks at CRS 2020. One 20 cm long soil core was taken in the center of the bed in each treatment plot and frozen until analyzed. Samples were extracted with 1 M KCl solution and submitted to the NC State Environmental and Agricultural Testing Service (EATS) laboratory for determination of soil NO_3-N and NH_4-N concentrations using a QuikChem IV flow-injection colorimetric analyzer (Lachat Instruments, Loveland, CO).

Treatment plots were harvested four times in each environment and cured in forced-air bulk curing barns according to standard curing protocols. Cured leaves were weighed and graded using the USDA grading scale which assigns a numerical quality index value (1-100) associated with leaf maturity and ripeness (Bowman et al., 1988) and conventional price indices (Fisher et. al, 2019). Value was calculated using conventional pricing structures to allow for comparison with the majority of flue-cured tobacco produced in North Carolina. Stand counts were collected after final harvest for adjusting yield data on a per-plant basis.

Statistical Analysis

All data were analyzed using the PROC GLIMMIX procedure in SAS v 9.4 (SAS Institute, Cary, NC). Each environment was analyzed separately. Residual plots and data distributions were examined to ensure the assumptions of ANOVA were met. Mulch treatment was treated as a fixed effect and block was treated as a random effect. Plant growth, aphid counts, and soil nitrogen data were analyzed as repeated measures with a heterogeneous autoregressive (ARH[1]) covariance structure. Least squared mean separation with Tukey's HSD adjustment at a significance of $p \leq 0.05$ was conducted when treatment was significant.

Due to being a proportion, average PAR reflectance data did not show a normal distribution and were thus analyzed using a beta distribution. The resultant Pearson chi-square/DF was equal to 1.0, indicating a proper fit for the selected distribution.

RESULTS AND DISCUSSION

Field Conditions

Weather patterns differed from thirty year historical averages in the study locations; at CRS in 2019, less than half of the typical amount of rain fell in May. June, and July, and the month of August also fell short of the thirty year average and overall precipitation for the season was about 85% of the average (Table 2.1). In 2020, May rainfall exceeded the thirty year average by 50% and 100% CRS and BBTRS, respectively. This trend continued in June at BBTRS while CRS received a normal amount of rain that month. Both locations experienced dry conditions in July 2020 with less than half the normal rainfall at CRS and approximately 70% of the average at BBTRS. Extreme weather events brought excess rainfall to both locations in August 2020, resulting in a total cumulative rainfall (April-August) exceeding the thirty year average by 16.4 cm (129%) at CRS and 28 cm (148%) at BBTRS. Although divergent from recent records, these conditions may be in line with growing conditions in coming years. Extreme rain events, overall precipitation and periodic severe drought are predicted to increase in North Carolina due to global climate change (Kunkel et al., 2020).

Average monthly temperatures were in line with historical data at CRS in 2019 and BBTRS 2020. CRS in 2020 experienced slightly cooler average temperatures in May and June, but in July returned to within 1°C of the thirty year average and remained typical for the rest of the growing season.

Plastic Mulch Optical Characteristics

Average PAR reflectance differed among the mulch treatments ($p = 0.0018$; Figure 2.1). The black, red, and bare ground treatments were not significantly different from each other and showed the lowest amount of PAR reflectance. Silver mulch reflected the highest amount of PAR (40.72%), which was significantly higher than black, red, and bare ground treatments. White mulch reflected 31.82% PAR, which was similar to the silver, red, and bare ground treatments but significantly higher than the black plastic treatment. Optical characteristics of the different mulch colors were in agreement with previous research where reflectance was measured. Differences in light reflectance and spectral distribution have been shown to impact both crop canopy and soil conditions during the growing season (Decoteau et al., 1988; Ballare et al., 1995; Lee et al., 1996).

Soil Temperature

Differences in CRS 2019 maximum daily soil temperature were observed in the mulch treatments throughout the growing season ($p < 0.0001$; Figure 2.2a). Silver mulch treatments were consistently cooler with average maximum temperatures from 27.7°C in May to 32.4°C in July. The bare ground without drip irrigation treatment was generally the hottest with temperatures ranging from 36.1°C in May to 37.5°C in July. The other mulch colors varied through the season but black tended towards hotter and white cooler. By August, all treatments had relatively high soil temperatures between 32.0°C and 34.8°C resulting in less separation among treatments. The monthly minimum temperatures showed a clear trend; red, black and silver mulches had consistently higher daily minimums compared to white and both bare ground treatments in all months ($p < 0.0001$; Figure 2.3a).

At CRS in 2020, black and red mulch treatments had significantly higher average monthly maximum temperature in April, May and June with temperatures approximately 25°C in April and May and 30°C in June ($P < 0.0001$ for all months; Figure 2.2b). In these early season months, the remaining mulch colors and bare ground treatments were clustered together with overall lower average monthly maximum temperatures, between 20.7°C and 22.2°C in April, 23.3°C and 25.7°C in May, and 26.6 and 27.8°C in June. In the final two months of the growing season all treatment monthly average maximum temperatures were clustered more tightly with two distinct groups forming: the mulched treatments were warmer, ranging from 32.0°C to 33.8°C in July and 30.2 to 31.3°C in August and the bare ground treatments were cooler in both months, with average maximum temperatures of 29.9°C and 30.6°C in July and approximately 28.5°C in August. Although separation among treatments in minimum monthly average temperatures was observed at CRS in both years, the magnitude of separation was less at CRS in 2020 but as in 2019, white mulch and both bare ground treatments were consistently cooler (Figure 2.3b).

Soil temperatures at BBTRS in 2020 followed similar trends; average maximums in black and red mulch treatments were significantly hotter than all others from May through August ($p < 0.0001$ for all months; Figure 2.2c). The average monthly minimums had less clear separation of means but continued the same pattern as observed in other environments with black and red treatments consistently the warmest and both bare ground treatments consistently the coolest in all months ($p < 0.0001$; Figure 2.3c). White and silver mulches had monthly minimum temperatures in between the two groups, with silver being warmer in June, July and August.

Most research on mulch color and soil temperature has been conducted using black, white, clear, or reflective mulches. Black mulches have been found to raise subsurface soil temperatures approximately 3°C at 10 cm belowground compared with bare soil, while white mulches were between 0.4°C and 4°C cooler than bare soil (Ham et al., 1993; Schonbeck and Evanylo, 1998; Lamont, 2017). Our results from 2020 are in agreement with prior findings. Specifically, black mulch was consistently between 3°C and 5°C warmer than bare ground without irrigation at 10 cm belowground. In CRS 2019, field conditions were exceptionally hot and dry (Table 2.1) and the bare ground without drip irrigation was warmest throughout the growing period, most likely due to the moisture holding capacity of the mulches and lack of water to buffer against high ambient temperatures in the bare ground without drip treatment.

Results of previous work are mixed regarding silver or reflective mulches. Lamont (2017) reported a slight decrease in soil temperature, while Ham et al. (1993) observed an increase in temperature similar to black mulch. This is also true in our studies. At CRS 2019, silver mulch was consistently much cooler than bare ground without irrigation: up to 8 °C at planting (Figure 2.2a and 2.3a). In the 2020 locations, silver mulch treatments had average monthly maximum temperatures approximately 2°C cooler than bare ground treatments at planting, but as the season progressed had a warming effect and in July and August the silver treatments had higher average monthly maximum temperatures than either bare ground treatment.

Soil Nitrogen

Soil nitrogen was only measured at the two 2020 locations. No significant interaction between days after transplant (DAT) and mulch treatment was observed in CRS 2020; however, both of the main effects significantly affected total soil nitrogen ($p < 0.0001$; Figure 2.4a). A decline in total soil nitrogen over time was observed and followed quadratic model. Silver and black treatments maintained significantly higher levels of total soil nitrogen than the two bare ground treatments, with the other mulch treatments nitrogen levels were in the middle. This pattern may be correlated with the average monthly minimum temperatures, as all mulched treatments maintained slightly higher minimum temperatures than the bare ground treatments. In April, May, and June, the monthly average minimum soil temperature for all treatments were below the optimum range for nitrification of 25 to 35°C, potentially slowing the conversion to plant-available nitrogen from the organic fertility source (Fig. 2.3a; Havlin et al., 2013). The mulched treatments all maintained slightly higher minimum temperatures than the bare ground treatments during these months and throughout the rest of the growing season, which may have resulted in a soil environment more conducive to mineralization of the organic fertilizer. Nitrogen mineralization rates highly correlated with soil temperature in agricultural soils (Miller & Geisseler, 2018). This finding could have implications for the rate of application of organic nitrogen fertilizers. If warmed soils are more conducive to nitrogen mineralization and therefore plant availability, rates of application could potentially be reduced.

In BBTRS there was a significant interaction between mulch treatment and DAT that followed a linear trend ($p = 0.0013$; Figure 2.4b). Total nitrogen levels in the bare ground treatments declined rapidly over the sampling period with slopes of -0.9514 mg kg^{-1} total nitrogen per DAT (bare ground with irrigation) and -1.6131 mg kg^{-1} total nitrogen per DAT (without irrigation). Mulched treatments maintained higher total nitrogen levels throughout with slopes ranging from -0.02041 (silver mulch) to 0.2071 (black mulch) mg kg^{-1} total nitrogen per DAT. Silver mulch maintained a higher level of total nitrogen throughout the sampling period, potentially due to more graduate mineralization and slower leaching in this location. Monthly rainfall in both locations exceeded the thirty year averages, with BBTRS receiving even more excessive precipitation (Table 2.1). We hypothesize that the strong negative slope observed in the bare ground treatments at BBTRS was related to extreme rainfall events as well as greater total rainfall in that location, which may have caused significant N leaching. As for the sustained higher levels of soil N in mulched treatments at BBTRS than CRS in 2020, all treatments in CRS received irrigation on a set schedule regardless of rainfall, while BBTRS received irrigation on an as-needed bases. It is likely that the excess irrigation applied in CRS contributed to N leaching in mulched treatments that did not occur in BBTRS. Caldwell et al. (2010) found that plastic mulch prevented rain penetration of the soil resulting in decreased soil N loss due to leaching. Though the mulches warmed the soil, the greater impact on N availability may have been the prevention of N leaching through the soil profile. In studies evaluating nitrate distribution in mulched versus unmulched treatments, earlier crop development and increased yields were attributed to the prevention of nutrient leaching below the root zone in mulched treatments (Filipovic et al., 2016; Chen, 2020). Due to the conflicting results and interference from differing levels of irrigation and rainfall, it is not possible to determine whether polyethylene mulches have a deleterious effect on the timing of nitrogen availability from organic fertilizer sources to flue-cured tobacco. However, extremely low post-harvest leaf tissue nitrate levels and reasonable yields suggest that higher levels of available nitrogen maintained in the mulched treatments did not negatively affect tobacco yield or quality (Table 2.6 and 2.7). Further research is needed for confirmation.

Plant Growth

Plant height was significantly affected by the interaction of DAT and mulch treatment ($p = 0.02$ CRS 2019; $p < 0.0001$ CRS 2020; $p < 0.0001$ BBTRS). Differences in plant height among the mulch treatments were not observed until 21 DAT in CRS 2019, 42 DAT in CRS 2020, and 41 DAT in BBTRS 2020 (Figure 2.5). All treatments with plastic mulch grew faster and taller than the bare ground treatments in all environments (Figure 2.5). Silver and white mulch treatments grew tallest in 2019, likely due to a warm early season (Table 2.1) that favored treatments that reflect heat and kept the soil cooler. Black mulch treatments grew taller in CRS 2020, potentially a result of cooler ambient temperatures in the early season. There is little research on the impact of polyethylene mulches on plant height in crops where yield is dependent on biomass production, but in studies of fruiting crops such as cucumber, tomato and bell pepper, red and black mulch produced higher crop biomass (Decoteau, 2008; Torres-Olivar et al., 2016). Franquera (2011) demonstrated that lettuce grown on red mulch produced the greatest leaf biomass, however the trial did not include a black mulch or bare ground treatments for comparison. The observed growth benefit of mulched treatments may also be associated with differing trends in N availability over the early season, where unmulched treatments had a significantly steeper decline in available N (Fig. 2.3), potentially limiting the rate of growth.

Differences in plant height were observed between bare ground with and without drip irrigation in CRS 2019 and BBTRS 2020 (Fig. 2.5 a & c); bare ground with irrigation grew taller than bare ground without irrigation, consistent with the irrigation benefit identified in a study on burley tobacco (Caldwell et al., 2010). This trend was not observed in CRS 2020, likely due to a less extreme dry period mid-season than occurred in CRS 2019 and BBTRS 2020.

Aphid presence

There was a significant interaction between mulch treatment and DAT for aphid count in CRS 2019 and BBTRS 2020 ($p < 0.0001$, Figure 2.6 a & c). Aphid counts in all treatments except silver mulch peaked 28 DAT in both CRS 2019 and BBTRS 2020. A smaller secondary peak occurred at 49 DAT in CRS 2019 and 41 DAT in BBTRS 2020 that included silver mulch. The silver mulch treatment had significantly lower aphid counts compared to all other mulches and bare ground with drip on the date of peak aphid counts in CRS 2019 and BBTRS 2020. This mulch treatment × DAT interaction was not observed in CRS 2020; however, the main effect of mulch treatment was significant ($p = 0.0003$; Fig. 2.6b). Despite the use of imidacloprid treated transplants in CRS 2020, overall aphid counts were similar to the other environments, likely because imidacloprid is a systemic insecticide that must be ingested and does not act as a repellant (Tomlin, 2006). The silver mulch treatment had lower aphid counts than the all other mulch colors and bare ground with irrigation (Figure 2.6). Interestingly, the silver treatment was not significantly different from bare ground without drip irrigation in any environment. Aphids are sucking insects attracted to succulent new growth and may not have been attracted to the stunted plants in unirrigated treatments (Burrack, 2014; Cao et al., 2018).

These results are consistent with results of previous studies that found highly reflective mulches impact insect pressure in the crop canopy (Matteson et al., 1992; Csizinszky et al., 1995). Other studies have demonstrated attraction and repulsion of aphid species by different colors of plastic mulches. Reflective silver mulch resulted in lower aphid populations and significantly decreased or delayed incidence of aphid vectored viral diseases in fruiting crops of up to 2 weeks in comparison to other mulch colors or bare ground treatments (Jones, 1991; Brown et al., 1993; Webb et al., 1994; Canul-Tun et al., 2017).

In-Row Weed Emergence and Biomass

Impacts on weed emergence and reduction of weed management labor is one of the most commonly referenced benefits of plasticulture with reported levels of control between 64% and 98% throughout a growing season, (Egley, 1983; Price & Norsworthy, 2013). In CRS 2019, weed emergence in red mulch treatments was greater than the other mulch colors and bare ground with irrigation ($p = 0.0002$), and weed biomass was significantly greater than all other treatments ($p < 0.0001$; Table 2.2). The red mulch used in this study yielded poor weed prevention due to it being semi-transparent and allowing for high levels of light transmission. These results are in agreement with Decoteau et al. (1988) and Bonanno (1996) who showed a direct correlation between weed emergence and colored mulches that still transmit high levels of light. Although weed emergence was between 157 and 1,025% greater in the bare ground treatments than in silver, black, and white treatments, and biomass between 325% and 1,500% greater, no statistical differences were observed due to the extreme levels of weed emergence and biomass in the red mulch treatments (Table 2.2). With historically low rainfall in May 2019 (Table 2.1), early season weed emergence was low on average and most notably in bare ground treatments where no weed management was employed.

Both locations in 2020 had less ambiguous results. With April, May, and June cumulative rainfall in excess of the 30 year historical average (Table 2.1), bare ground treatments with and without drip irrigation had average weed emergence in the hundreds or thousands of individual weeds per square meter and in excess of 500 g m^{-2} in both locations (Table 2.2). Weed emergence in the silver, black, and white treatments was essentially zero in the 2020 environments, with a few weeds observed in white mulch in BBTRS (Table 2.2). Red mulch again had higher weed emergence in both locations, though not significantly different from the other mulched treatments in comparison with bare ground. In CRS 2020, bare ground treatments with and without drip irrigation exceeded the level of red mulch weed emergence by more than five-fold and weed biomass by more than twenty-fold. In BBTRS 2020, emergence in bare ground treatments exceeded the level in red mulch treatment by 3.3-fold and biomass by at least 11-fold.

Yield, Quality and Value

Yield: CRS 2019 yield was not different among treatments except for the red plastic mulch, which yielded approximately 50% that of the other mulch colors ($p = 0.0067$; Table 2.7). This can be attributed to heavy weed pressure under the red mulch treatments (Table 2.2), which is consistent with previous work showing that infrared and far-red reflecting mulches have reduced weed suppression ability in comparison with fully opaque mulches (Decoteau et al., 1988; Bonanno, 1996). Lower than normal average rainfall in 2019 (Table 2.1) was not conducive to weed germination and growth in our bare ground treatments (Table 2.2). We believe that the lack of differences observed between the bare ground treatments' yields and that of white, black, and silver mulches was due to minimal weed competition in bare ground treatments.

In CRS 2020, the treatments separated into three groups: silver, black and white mulch treatments yielded the highest, between 1,963 and 2,217 kg ha^{-1} followed by red mulch (1,277 kg ha^{-1}). Both bare ground treatments yielded significantly less than any mulched treatment: 244 kg ha^{-1} with irrigation and 67 kg ha^{-1} without ($p < 0.0001$). Mulched treatments yielded between 520 and 890% more than the bare ground with drip irrigation, exceeding results of vegetable crop trials where mulch exceeded bare ground by 150 to 500% (Farias-Larios & Orozco-Santos, 1997; Schonbeck & Evanylo, 1998; Sanders, 2001; Ibarra-Jiménez et al., 2008).

In BBTRS 2020, all mulched treatments yielded approximately the same and were between 290 and 398% higher than bare ground with irrigation and between 394% and 535% higher than bare ground without irrigation ($p = 0.0047$). With high weed pressure conditions in both locations in 2020, all mulch colors offered a yield benefit. Cool, wet conditions in 2020 may have also contributed to the observed mulch-related yield benefit when compared with hot, dry conditions in 2019. Higher growth rates and subsequent yields in all mulch treatments when compared with bare ground treatments may be attributed to several variables including soil warming (Figure 2.2 & 2.3), reduced weed pressure (Table 2.2) and particularly in BBTRS, a less drastic decrease in plant available nitrogen (Figure 2.4). Tobacco yields are significantly reduced by weed competition (Wilson, 1955; Ian et al., 2013; Vann et al., 2021) and lower total available N in the early part of the growing season (Collins & Hawks, 1993).

When biomass production of fruiting crops was investigated, red and black mulches resulted in higher leaf biomass production (Decoteau, 2008; Torres-Olivar et al., 2016). While not the primary goal for fruiting crops, increased biomass production in tobacco translates directly into increased yield because plant height and number of leaves have been shown to be positively and significantly correlated with cured leaf yield (Sastry & Gopinath, 1969).

The North Carolina flue-cured tobacco average yield was 2,242 kg ha^{-1} in 2019 and 2,018 kg ha^{-1} in 2020 (USDA-NASS & NCDACS, 2021). All treatments except red mulch were roughly equivalent to the average in 2019 (Table 2.7). In 2020, all mulched treatments in both locations surpassed the state average yield except red mulch at CRS. Comparison of the bare ground treatments with state averages did not show a consistent trend but were generally lower in CRS 2020 and BBTRS 2020, both bare ground treatments yielded below statewide average, while in CRS 2019 the bare ground treatments with irrigation yielded above the statewide average and the bare ground treatments without irrigation yielded below the statewide average.

Quality: In CRS 2019 and 2020, leaf quality from mulched treatments was significantly higher than the bare ground without drip irrigation; quality indices were approximately 130% and 400% higher in 2019 and 2020, respectively ($p = 0.0046$; Table 2.7) While mulch treatments were not statistically different from bare ground with drip irrigation in CRS 2020, the quality indices of mulched treatments exceeded the bare ground with irrigation by 145%. These two groups were equivalent in 2019. There were no quality differences among any treatments in BBTRS 2020 ($p = 0.058$). Tobacco crop quality is generally associated with the proper timing of N deprivation and harvest (McCants & Woltz, 1967). The 2020 results do not indicate that availability of N in the midseason, which was higher in mulched plots, reduced quality at harvest. Observing the lowest quality harvest in unirrigated treatments as in CRS 2019 and 2020 is consistent with research showing that reduced crop quality is associated with drought stress (Weybrew & Woltz, 1975; Campbell et al., 1982; Peedin, 1999).

Value: Value analysis is based on conventional pricing due to the complexity of obtaining accurate organic pricing. In CRS 2019, the values of silver, white, black mulch treatments and bare ground with irrigation were similar and very low due to the challenging growing season. Either crop yield or quality must vary significantly to impact overall value. Bare ground with drip irrigation had the highest value and bare ground without irrigation had the lowest, with the other mulch treatments in between ($p = 0.0008$; Table 2.7). These differences were dictated by yield due to lack of difference in quality indices among treatments in this environment (Table 2.7). The reduced value of the red mulch treatment can be attributed to the significantly high weed pressure (Table 2.2). In both 2020 locations, two distinct groupings formed in the value data: all mulched treatments resulted in higher valued crop than both bare ground treatments (BBTRS $p = 0.0093$; CRS $p < 0.0001$; Table 2.7).

Treatment differences in crop value can be attributed to the observed differences in soil temperature, total available N, and weed pressure. In 2020, the lower yield from bare ground treatments was most likely a result of the significantly higher weed pressure observed in these treatments (Table 2.2), mirroring what was observed in the red mulch treatment in 2019. However, the differences in available N(significantly lower in bare ground treatments) likely also contributed to subsequent differences in value, as well as the different mulch colors contributing to warmed soil temperature in the cooler season (2020) and cooled soil in the warmer season (2019). With all mulched treatments approximately equivalent in value in 2020, differences between the mulch colors do not seem to have had a practical effect.

Leaf Chemistry

***Total alkaloids*:** There were no differences among treatments in total alkaloids at topping at either location in 2020, treatment based differences emerged in post-harvest composite measurements (BBRTS $p = 0.3724$*;* CRS $p = 0.4127$*;* Table 2.3). In CRS 2019 post-harvest composite leaf samples, total alkaloid concentrations ranged from 1.63% to 2.69% with white mulch at the lower end, distinct from bare ground without drip irrigation at the high end ($p = 0.0249$; Table 2.4). Bare ground treatments with drip irrigation in 2020 had lower total alkaloid concentrations than silver and black mulches in BBTRS ($p = 0.0104$) and silver, black and white mulches in CRS ($p = 0.001$). These results may be due to lower amounts of available N in the bare ground treatments in 2020, soil nitrogen data are not available for 2019 but with less overall rainfall there may have been lower nitrate leaching in that environment (Figure 2.4). Previous work has shown that higher levels of available soil N throughout the growing season was correlated with increased total alkaloids (Weybrew et al., 1983). Although high levels of alkaloids are associated with undesirable smoking characteristics, total alkaloids did not exceed 3.5% in any treatment in any environment, which can be associated with poor quality (Collins & Hawks, 1993).

Reducing Sugars: All treatments had similar levels of reducing sugars at topping and post-harvest except at topping in BBTRS 2020 (Table 2.3 and 2.4). Because mid-season samples were analyzed without curing, these differences are not meaningful. Post-harvest composite sample levels ranged from 12.77% to 19.52% with bare ground treatments trending lower and mulched treatments trending higher; however, there were no differences among treatments at any location ($p > 0.05$ for all locations).

Leaf Nitrates: Leaf nitrate concentrations were highly variable and generally low in all locations. In CRS 2019 only bare ground without drip irrigation had statistically higher leaf nitrate levels at topping with 14,427 mg kg^{-1} NO_3. Nitrate concentrations of the remaining treatments ranged between 2,638 and 8,793 mg kg^{-1} with red mulch on the low end and the silver mulch treatment at the high end ($p < 0.0001$; Table 2.5). This difference is potentially due to the smaller size of the unirrigated bare ground plants compared with the other treatments. In CRS and BBTRS 2020 there were no differences among treatment NO_3^- concentrations at topping or post-curing, nearly all values were below the detection limit of 55.5 mg kg^{-1} NO_3^- ($p > 0.5$; Table 2.5 and 2.6). High variability in the results is possibly due to differing growth stages between treatments at sampling. Low nitrate content of cured leaves in this study is consistent with the results found in another study of tobacco grown under plasticulture, where increased soil moisture levels of irrigated, mulched tobacco yielded significantly lower tobacco specific nitrosamines in burley tobacco (Caldwell et al., 2010). This is likely due to excessive irrigation leading to leaching of soil N and lower availability to the crop. Leaf NO_3^- has been found to correlate with root zone temperature more strongly than with than soil NO_3^- concentration (Osmond & Raper, 1981). Although both variables differed among treatments in this study, they did not directly correlate with leaf NO_3^- levels.

CONCLUSION

This study is the first to evaluate the use of plasticulture and drip irrigation in organic flue-cured tobacco production. The results are consistent with previous plasticulture research in other cropping systems, confirming the factors that make plasticulture well suited to intensively managed, high value crop production and provide support for further exploration of the use of this system in flue-cured tobacco production in North Carolina. Two consecutive years of data show that black, white and silver polyethylene mulch provide a range of benefits over bare ground production. These varied by much color and included decreased weed populations, a soil warming effect in the early growing season, and maintained N levels due to altered soil temperature and moisture status or via prevention of premature nutrient leaching due to extreme rainfall. These impacts ultimately resulted in faster plant growth over bare ground treatments, depending on mulch color and environment. The reflective silver mulch had an added benefit of disrupting aphid populations. The study results indicate that the excellent weed emergence prevention offered by the opaque mulches drove higher yields in the environments with normal to excessive rainfall. There are other potential benefits, such as taking advantage of the soil warming benefit of certain mulch colors to allow earlier planting. More research is warranted to optimize the plasticulture system for flue-cured tobacco including comparison with traditional weed management, mulch impacts on soil health and economics of integration of plasticulture with organic flue-cured tobacco production. This information will allow for advancement in organic flue-cured tobacco production and support understanding of mulch-crop interaction.

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Table 2.1 Cumulative rainfall and average temperature by month compared to the 30 year monthly cumulative average at Cunningham Research Station, Kinston, NC and Border Belt Tobacco Research Station, Whiteville, NC.

Location	**April**		**May**		**June**		**July**		**August**		**Total**
	Rainfall (cm)	℃	Rainfall (cm)	℃	Rainfall (cm)	℃	Rainfall (cm)	℃	Rainfall (cm)	℃	Rainfall (cm)
CRS 2019	8.1	17.8	4.3	24.0	13.3	24.7	12.0	27.2	11.7	25.3	49.4
CRS 2020	12.1	15.7	15.3	19.0	12.5	23.8	5.8	27.3	26.4	26.0	72.1
BBTRS 2020	9.7	16.7	25.5	19.8	23.2	24.0	9.7	27.2	18.0	25.9	86.1
CRS 30 yr[a]	8.0	17.2	9.4	21.4	12.9	25.6	14.2	27.2	13.7	26.4	55.7
BBTRS 30 yr	7.7	16.1	10.7	20.7	11.4	24.8	14.0	26.6	14.3	25.8	58.1

[a] 30-year averages calculated from 1981-2010 data taken from NCEI COOP stations located closest to respective ECONet stations

Table 2.2 Mulch treatment effect on weed emergence and biomass at Cunningham Research Station, Kinston, NC and Border Belt Tobacco Research Station, Whiteville, NC.

	CRS 2019		**CRS 2020**		**BBTRS 2020**	
Treatment[a]	**Weed emergence**[b] **(# m^{-2})**	**Weed biomass (g m^{-2})**	**Weed emergence (# m^{-2})**	**Weed biomass (g m^{-2})**	**Weed emergence (# m^{-2})**	**Weed biomass (g m^{-2})**
Silver	67 b[c]	4 b	0 b	0 b	0 b	0 b
Black	16 b	1 b	0 b	0 b	0 b	0 b
Red	323 a	197 a	126 b	37 b	298 b	43 b
White	46 b	1 b	0 b	0 b	0 b	0 b
Bare ground +drip	105 b	15 b	646 a	806 a	1001 a	553 a
Bare ground -drip	164 ab	13 b	678 a	998 a	1403 a	479 a

[a] All colored mulch treatments and bare ground control with drip received the same amount of irrigation.

[b] Seedlings per m^2 at approximately one month after transplant.

[c] Means followed by the same letter within year and location are not different (Tukey's honest significant difference; $\alpha = 0.05$) and represent the average of four replications (CRS 2019 and 2020; n = 4 data points for each mean) or three replications (BBTRS; n=3 data points for each mean).

Table 2.3 Mulch treatment effect on total alkaloids and reducing sugars at topping in Cunningham Research Station, Kinston, NC and Border Belt Tobacco Research Station, Whiteville, NC in 2020.

	CRS 2020		**BBTRS 2020**	
Treatment	**Total Alkaloids**	**Reducing Sugars**	**Total Alkaloids**	**Reducing Sugars**
	%			
Silver	0.45	6.75	0.17	3.34 c[a]
Black	0.43	7.01	0.22	4.78 bc
Red	0.35	7.08	0.18	4.89 bc
White	0.31	6.51	0.23	4.64 bc
Bare ground +drip	0.42	8.51	0.17	7.66 ab
Bare ground -drip	0.40	7.79	0.24	9.85 a

[a] Means followed by the same letter within response and location are not different (Tukey's honest significant difference; $\alpha = 0.05$) and represent the average of four replications (CRS) or three replications (BBTRS) and 5 treatment subsamples (n = 20 data points for each mean at CRS and n = 15 for each mean at BBTRS).

Table 2.4 Mulch treatment effect on tobacco leaf total alkaloids and reducing sugars at post-curing in Cunningham Research Station, Kinston, NC and Border Belt Tobacco Research Station, Whiteville, NC 2019 and 2020.

	CRS 2019		**CRS 2020**		**BBTRS 2020**	
Treatment	**Total Alkaloids**	**Reducing Sugars**	**Total Alkaloids**	**Reducing Sugars**	**Total Alkaloids**	**Reducing Sugars**
	——————————————————%——————————————————					
Silver	2.23 ab[a]	17.39	2.09 a	19.52	2.40 ab	15.47
Black	1.77 ab	17.63	1.81 ab	18.67	2.56 a	13.74
Red	1.71 ab	17.75	1.66 abc	18.20	2.13 abc	18.58
White	1.63 b	17.10	1.87 ab	18.01	2.12 abc	16.34
Bare ground +drip	2.28 ab	18.26	1.21 c	15.84	1.46 c	12.82
Bare ground -drip	2.69 a	12.77	1.29 bc	19.34	1.65 bc	13.82

[a] Means followed by the same letter within response are not different (Tukey’s honest significant difference; $\alpha = 0.05$) and represent the average of four replications (CRS) or three replications (BBTRS) and 5 treatment subsamples (n = 20 data points for each mean at CRS and n = 15 for each mean at BBTRS).

Table 2.5 Mulch treatment effect on leaf tissue nitrates at topping in Cunningham Research Station, Kinston, NC and Border Belt Tobacco Research Station, Whiteville, NC 2019 and 2020.

	CRS 2019	**CRS 2020**	**BBTRS 2020**
Treatment[a]	**Tissue Nitrates (mg kg^{-1})**	**Tissue Nitrates (mg kg^{-1})**	**Tissue Nitrates (mg kg^{-1})**
Silver	8,793.29 b[b]	69.16	3,401.69
Black	6,491.42 bc	0	11,296.20
Red	2,638.10 c	0	70.34
White	8,565.59 b	0	3,354.14
Bare ground +drip	4,203.25 bc	0	2,104.17
Bare ground -drip	14,427.00 a	0	135.80

[a] All colored mulch treatments and bare ground control with drip received the same amount of irrigation

[b] Means followed by the same letter within response are not different (Tukey's honest significant difference; α = 0.05) and represent the average of four replications (CRS) or three replications (BBTRS) and 5 treatment subsamples (n = 20 data points for each mean at CRS and n = 15 for each mean at BBTRS).

Table 2.6 Mulch treatment effects on post-harvest measurements of leaf tissue nitrates in Cunningham Research Station, Kinston, NC and Border Belt Tobacco Research Station, Whiteville, NC 2019 and 2020.

	CRS 2019	**CRS 2020**	**BBTRS 2020**
Treatment[a]	**Tissue Nitrates (mg kg^{-1})**	**Tissue Nitrates (mg kg^{-1})**	**Tissue Nitrates (mg kg^{-1})**
Silver	906.66	186.85	196.17
Black	0	0	27.75
Red	0	0	390.31
White	0	101.55	403.83
Bare ground +drip	0	48.07	0
Bare ground -drip	932.56	66.45	0

[a] All colored mulch treatments and bareground control with drip received the same amount of irrigation

[b] Means followed by the same letter within response are not different (Tukey's honest significant difference; α = 0.05) and represent the average of four replications (CRS) or three replications (BBTRS) and 5 treatment subsamples (n = 20 data points for each mean at CRS and n = 15 for each mean at BBTRS).

[c] Mulch treatement effects were not significant in this environment.

Table 2.7 Effect of mulch treatment on tobacco leaf yield, quality and value in Cunningham Research Station, Kinston, NC and Border Belt Tobacco Research Station, Whiteville, NC 2019 and 2020.

	CRS 2019			**CRS 2020**			**BBTRS 2020**		
Treatment[a]	**Yield (kg ha^{-1})**	**Quality Index**	**Value (USD ha^{-1})**	**Yield (kg ha^{-1})**	**Quality Index**	**Value (USD ha^{-1})**	**Yield (kg ha^{-1})**	**Quality Index**	**Value (USD ha^{-1})**
Silver	2,289 a[b]	56 a	5,384 ab	2,217 a	85 a	8,758 a	2,955 ab	87 a	11,739 a
Black	2,231 a	56 a	5,179 ab	1,963 a	81 a	7,271 ab	3,523 a	86 a	14,203 a
Red	1,277 b	58 a	3,145 c	1,277 b	81 a	4,705 b	2,595 abc	86 a	10,134 a
White	2,143 a	56 a	4,968 ab	2,157 a	80 a	7,909 ab	3,190 ab	85 a	12,616 a
Bare ground +drip	2,433 a	58 a	5,747 a	244 c	55 ab	819 c	898 bc	72 a	3,175 b
Bare ground -drip	2,160 a	43 b	1,616 bc	67 c	21 b	234 c	659 c	72 a	2,364 b

[a] All colored mulch treatments and bare ground control with drip received the same amount of irrigation

[b] Means followed by the same letter within response are not different (Tukey's honest significant difference; $\alpha = 0.05$) and represent the average of four replications (CRS) or three replications (BBTRS) and approximately 20 subsamples (varied by location and treatment plot) (n = 80 data points for each mean at CRS and n = 60 for each mean at BBTRS).

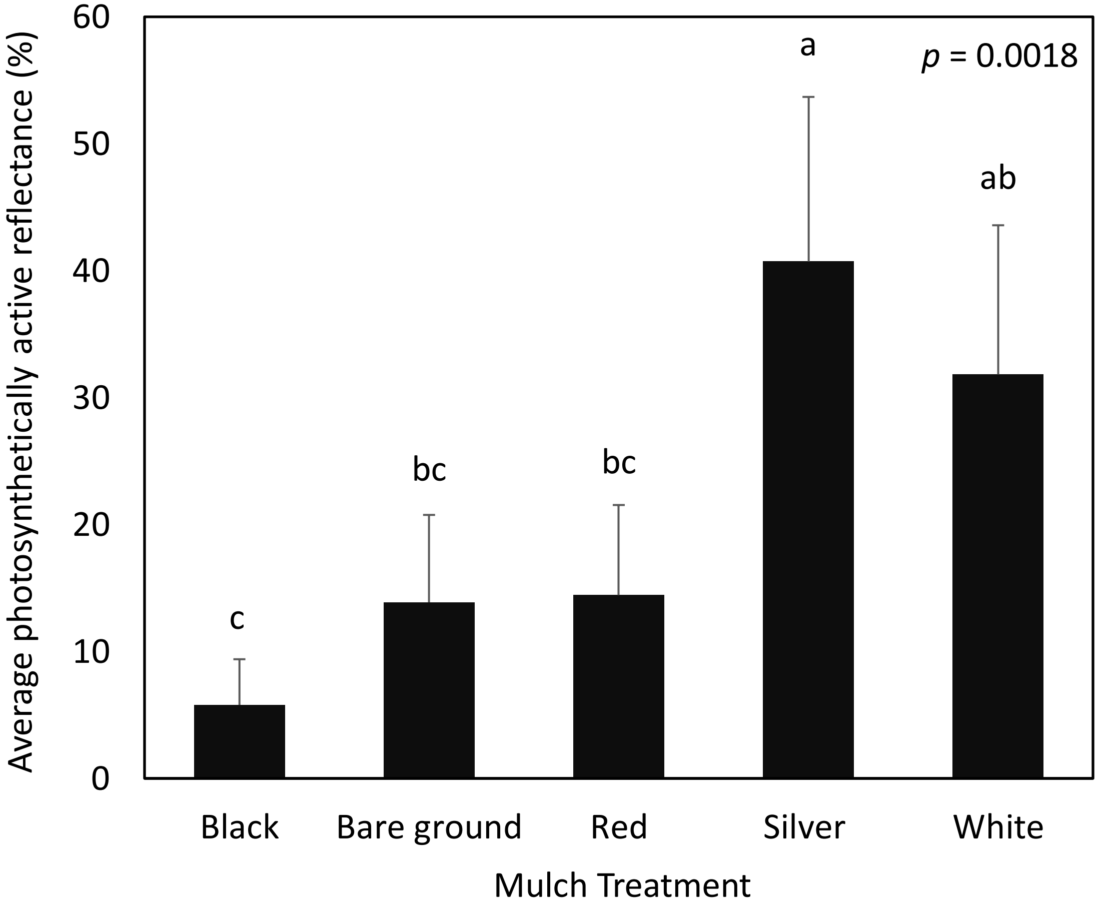

Figure 2.1 Main effect of mulch treatment on average photosynthetically active reflectance ± standard error in May 2019 at Cunningham Research Station, Kinston, NC. Means followed by the same letter are not different (Tukey's honest significant difference; $\alpha = 0.05$) and represent the average of four replications (n = 4 data points for each mean).

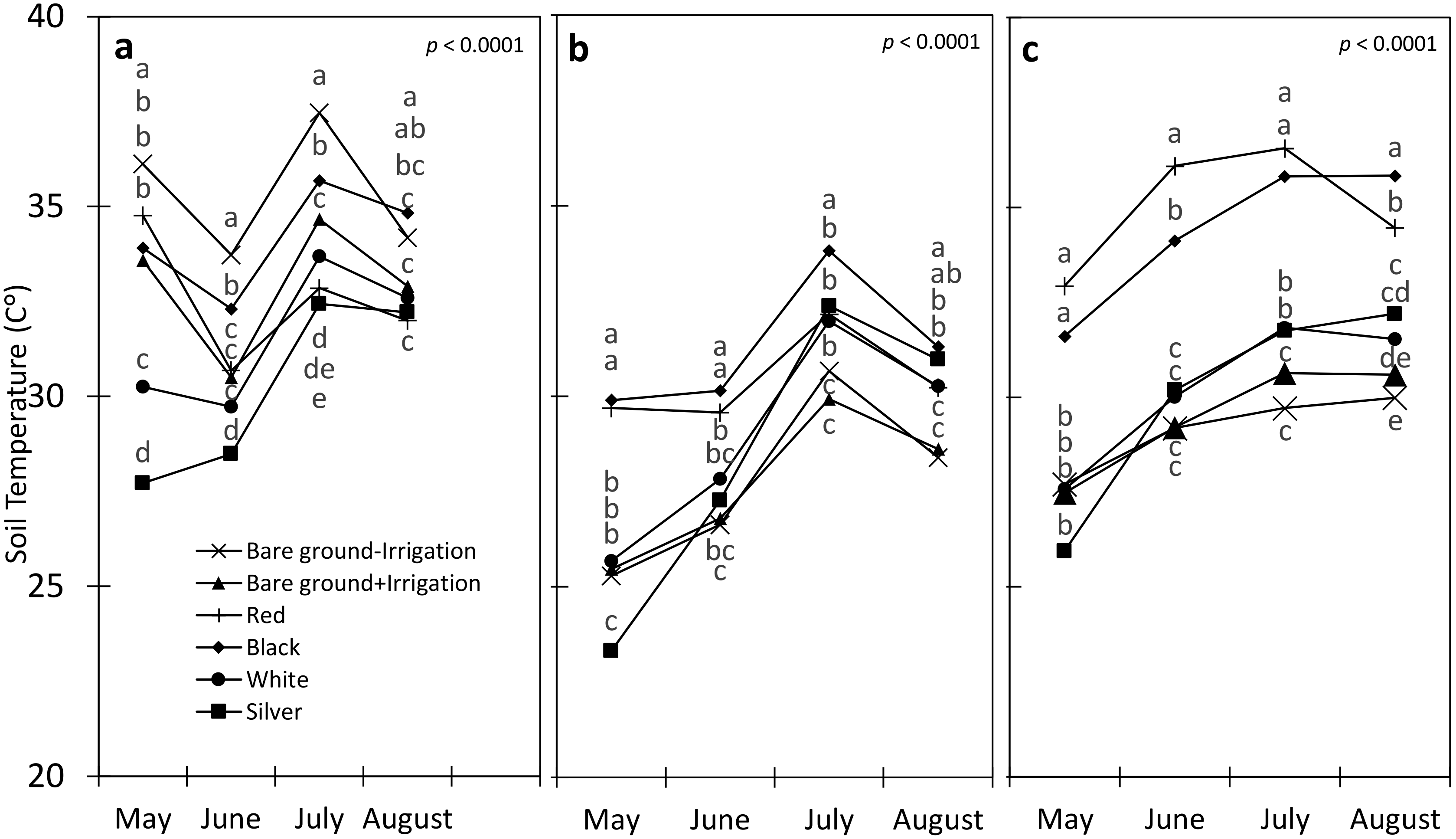

Figure 2.2 Effects of mulch treatments on average maximum soil temperature 10 cm below ground at CRS in 2019 (a), CRS in 2020 (b), and BBTRS 2020 (c). Means followed by the same letter within location and month are not different (Tukey's honest significant difference; α = 0.05) and represent the average of four replications (CRS 2019 and 2020) or three replications (BBTRS) and 30 or 31 treatment subsample (n = 120 or 124 data points for each mean at CRS and n = 90 or 93 for each mean at BBTRS).

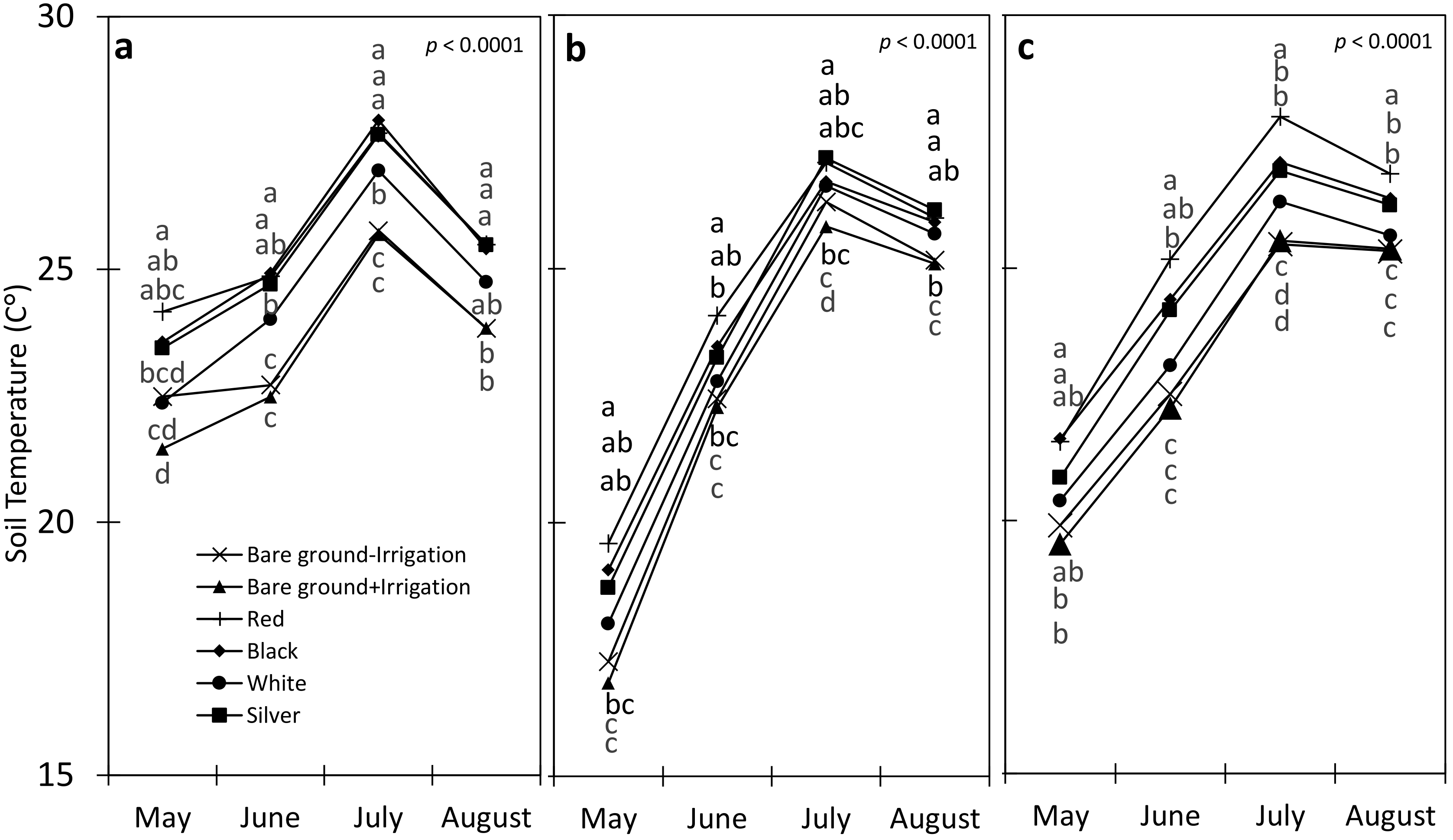

Figure 2.3 Effects of mulch treatments on average minimum soil temperature 10 cm below ground at CRS in 2019 (a), CRS in 2020 (b), and BBTRS 2020 (c). Means followed by the same letter within location and month are not different (Tukey's honest significant difference; $\alpha = 0.05$) and represent the average of four replications (CRS 2019 and 2020) or three replications (BBTRS) and 30 or 31 treatment subsample (n = 120 or 124 data points for each mean at CRS and n = 90 or 93 for each mean at BBTRS).

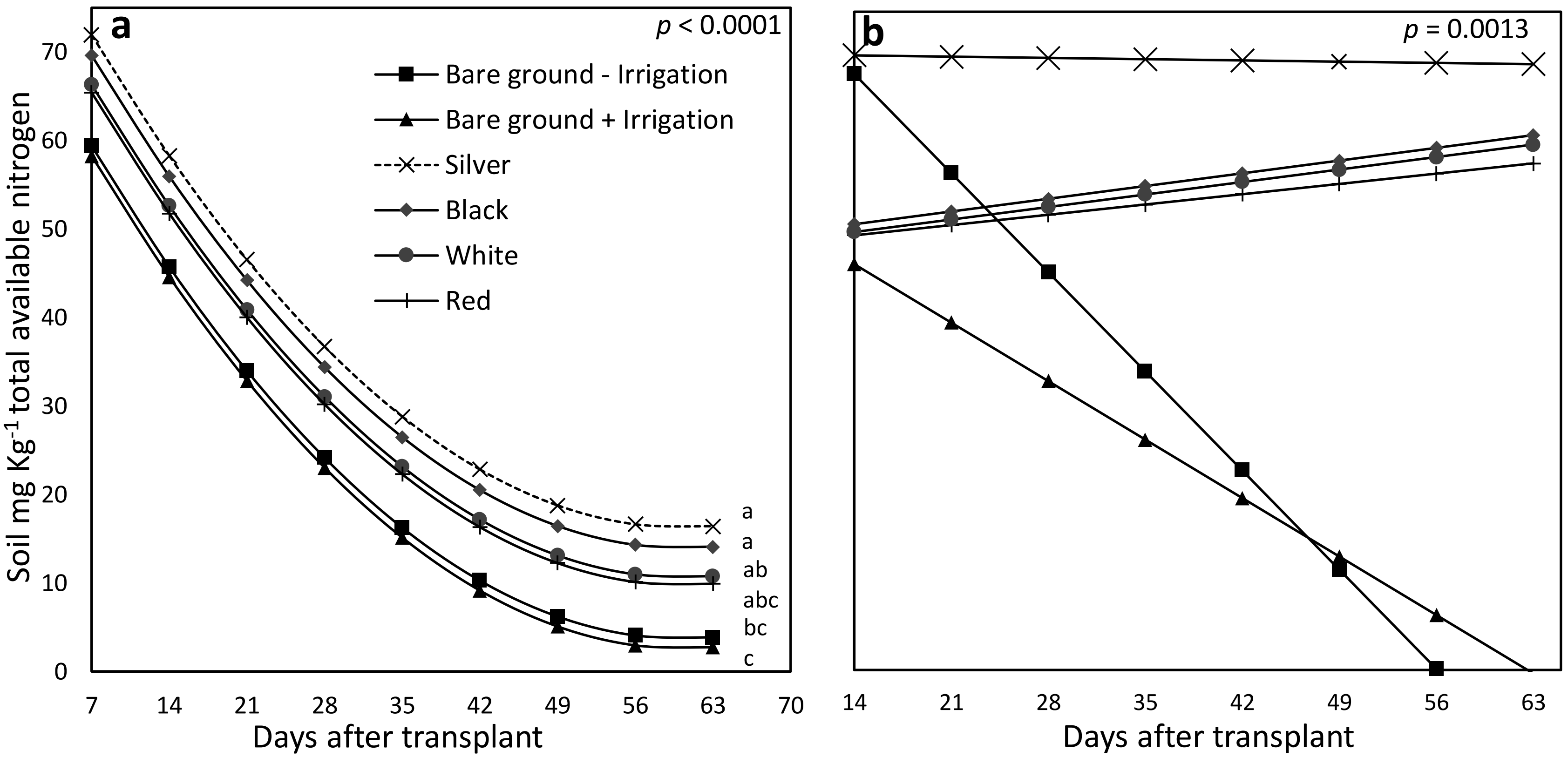

Figure 2.4 1. Fixed effects regression models for total available soil nitrogen from 7 days after transplant at CRS in Kinston, NC in 2020 (a**)** and total available soil nitrogen from 14 days after transplant at BBTRS in Whiteville, NC in 2020 (b). Main effects of days after transplant and mulch treatment were significant at CRS in 2020. Means followed by the same letter at CRS are not different (Tukey's honest significant difference; $\alpha = 0.05$) and represent the average of four replications (CRS) or three replications (BBTRS). The interaction of days after transplant and mulch treatment was significant at BBTRS.

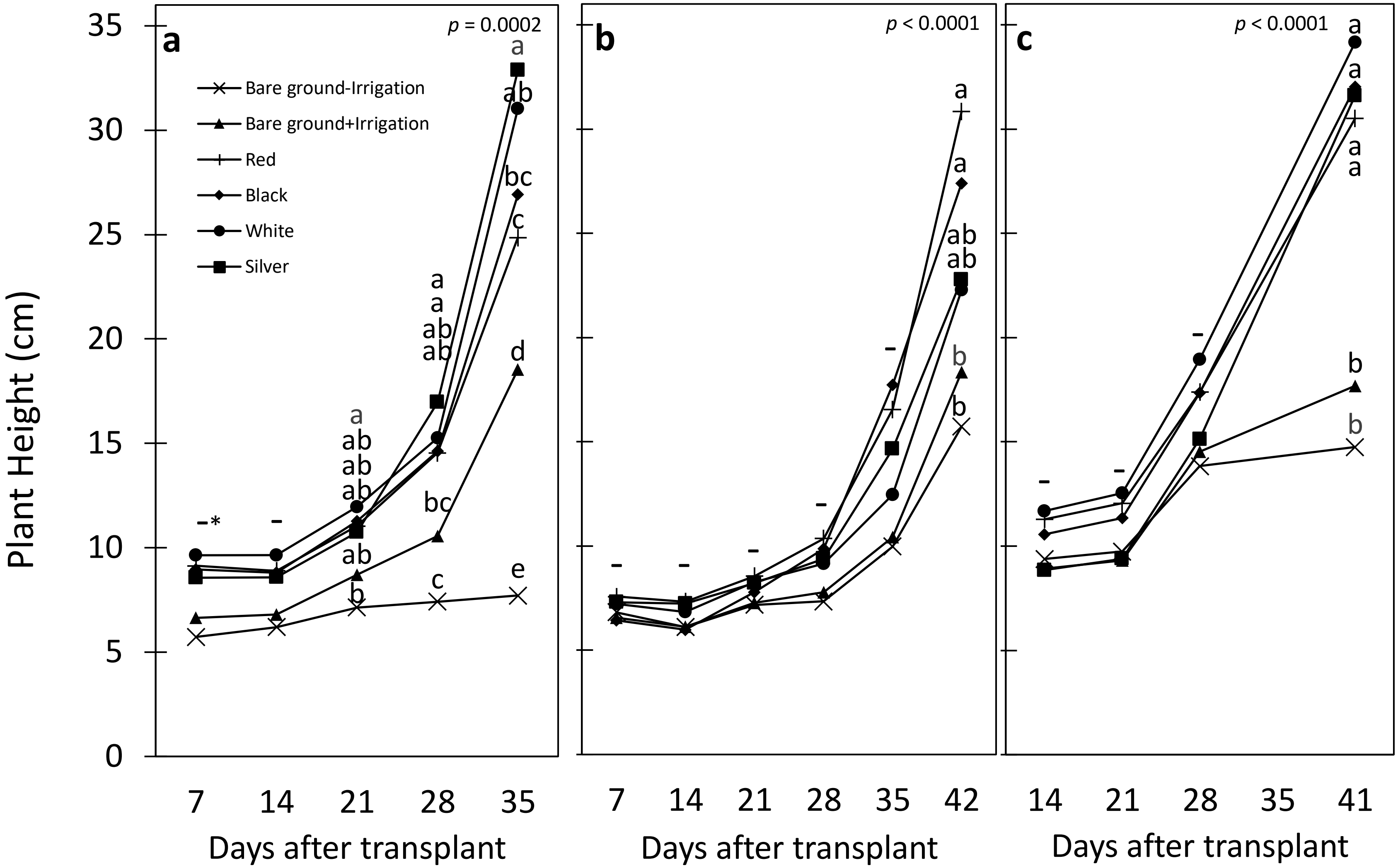

Figure 2.5 Effects of days after transplant and mulch treatment on plant growth at CRS in 2019 (a), CRS in 2020 (b), and BBTRS in 2020 (c). Data for 35 DAT at BBTRS 2020 unavailable. Means followed by the same letter are not different (Tukey's honest significant difference; α = 0.05) and represent the average of four replications (CRS 2019 and 2020) or three replications (BBTRS) and 10 plants per plot (n = 40 at CRS, n = 30 at BBTRS). *Indicates no difference among treatment means within a day after transplant.

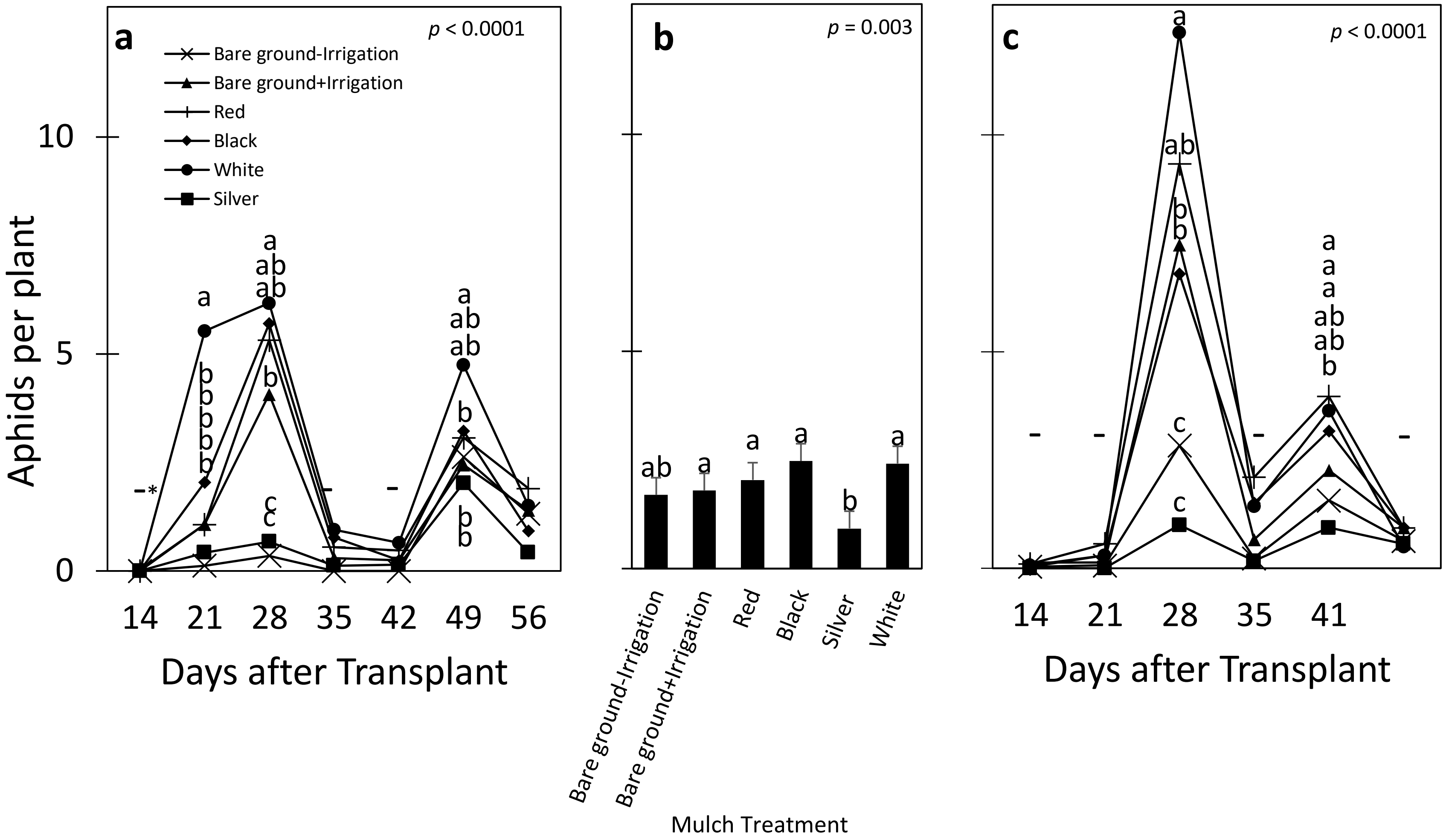

Figure 2.6 Effects of days after transplant and mulch treatment on aphid count at CRS in 2019 (a), BBTRS in 2020 (c) and main effect of mulch treatment on aphid count at CRS in 2020 (b). Means followed by the same letter are not different (Tukey's honest significant difference; α = 0.05) and represent the average of four replications (CRS 2019) or three replications (BBTRS) and 10 plants per plot (n = 40 at CRS in 2019, n = 30 at BBTRS). The mulch treatment × DAT interaction was not observed at CRS 2020 and means represent the average of four replications, six dates, and 10 plants per plot (n = 240). *Indicates no difference among treatment means within a day after transplan

CHAPTER THREE

EVALUATION OF THE USE OF CONSERVATION TILLAGE PRACTICES IN THE PRODUCTION OF ORGANIC FLUE-CURED TOBACCO (Nicotiana tabacum L.)

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ABSTRACT

Intensive tillage in flue-cured tobacco contributes to soil erosion and reduced water-holding capacity of soils. Conservation tillage minimizes soil disturbance by planting a crop directly into the residue of overwintered cover crop. Reducing tillage has been shown to improve soil health (increased rainwater infiltration, improved water-holding capacity, reduced erosion), reduced production costs (fuel and labor). The cover crop mulch layer may also prevent weed emergence. The objective of this study was to compare the effects of conservation and conventional tillage on weed management in flue-cured tobacco grown without herbicides as in organic management.

Field studies were conducted at the Cunningham Research Station in Kinston, NC in 2019 and 2020 and at the Upper Coastal Plain Research Station in Rocky Mount, NC in 2020, comparing the impacts of conventional tillage and conservation tillage on weed emergence and tobacco production. An overwintered cereal rye (*Secale cereal*) cover crop was conventionally tilled or terminated via roller-crimper and left in place as a mulch prior to transplant of flue-cured tobacco. Cover crop biomass, weed emergence and biomass, soil resistance, yield, quality and cured leaf chemistry were evaluated. In all environments, conservation tillage with cover crop mulch reduced weed density and biomass when compared to conventional treatments. In 2019, cured leaf yield was higher under conservation tillage practices than conventional. In 2020, environmental conditions in both locations resulted in crop loss.

These results indicate that conservation tillage practices may be an effective weed management strategy, while improving yields in an organic production system. However, organic flue-cured tobacco grown under conservation tillage is vulnerable to environmental challenges due to the exclusion of in-season cultivation.

INTRODUCTION

The North Carolina state economy is driven by agriculture. Flue-cured tobacco (*Nicotiana tabacum* L.) has been a key component of the state's agricultural production for several centuries, peaking at 341,000 hectares in 1939 (USDA-NASS & NCDACS 2020). The state ranks first in U.S. flue-cured tobacco production, accounting for 78.7% of total U.S. production in 2019 with 106 million kg grown (USDA-NASS & NCDACS, 2020). Due to decreased domestic demand and increased supply from abroad, production has declined over the last several decades to just 47,000 hectares in 2019 and the future of flue-cured tobacco remains uncertain (USDA-NASS & NCDACS 2020). U.S. flue-cured tobacco production that year reached a 100 year low at 134 million kilograms, a decline that is unlikely to reverse (Brown, 2021). Aside from diversifying, switching crops, or selling the farm, converting conventional tobacco production to certified organic is an option that has kept some farming families in North Carolina in business (Little et al., 2018). Although certified organic flue-cured tobacco constitutes just 5% of the total flue-cured tobacco crop in the state, increasing demand for organic product has resulted in higher prices that support the increased cost of production and helps growers offset reduced income due to decreased demand for conventionally produced flue-cured tobacco. Certified organic flue-cured tobacco sold for \$7.21 kg^{-1} in North Carolina in 2017 while the average price for conventional flue-cured tobacco has averaged under \$4.30 kg^{-1} over the last five years (USDA-NASS & NCDACS, 2020; Vann et al., 2019). Approximately 64% of the U.S. certified organic flue-cured tobacco crop was grown on 119 farms in North Carolina in 2019, about 5.4 million kg with a farm-gate value of \$39 million, (USDA-NASS, 2017; Vann et al., 2019).

Most of the tobacco production history in the U.S. would have been considered organically grown without technologies developed in the 20th century (Kohrman & Benson, 2011). Over the last several decades, mechanization, modern synthetic fertilizers and pesticides, and genetic improvements have increased yield and leaf quality (Bowman et al., 1984). When demand for chemical-free and organic tobacco emerged in the 1980s in the southwestern U.S, growers in the highly productive southeast were approached to revive the growing practices from the generations prior (Little et al., 2008). Flue-cured tobacco is a challenging crop to grow well in either growing system. The restrictions of organic certification add a layer of complexity because growers must rely on systems-based fertility and pest management, limited to materials allowed by the Organic Materials Review Institute (OMRI) for use under the USDA National Organic Program (USDA-NOP, 2016). Organic pest management requires an integrated approach to achieve successful yield and quality (Bond & Grundy, 2001).

Tillage, cultivation and mulching are the primary weed management tools used in organic production of many crops (Bond & Grundy, 2001). Conventional weed management in tobacco also relies on integrated tools to make the most of the seven registered herbicides by combining cultural techniques including deep tillage and cultivation (Gooden et al., 2008; Vann et al., 2021). As with any integrated management approach, a variety of strategies are utilized to prevent weed emergence, especially during the critical period for weed control between two and 6.5 weeks after transplant (Inman et al., 2018). As the risk of herbicide resistance grows, alternative strategies become increasingly important to manage weed populations that have already developed resistant biotypes such as *Amaranthus* sp. weeds, a troublesome weed throughout the United States, particularly in the southeast (Ward, 2013).

Intensive tillage is common in both conventional and organic flue-cured tobacco production for purposes beyond weed management. It is utilized in field preparation, raised bed formation, and post-transplant cultivations to prevent soil clodding and promote soil drainage in addition to weed management (Britt & Slater, 1957; Vepraskas & Miner, 1986; Bathke et al., 1993; Collins & Hawks, 1993; Flower, 2001; Troeh & Thompson, 2005, Gooden et al., 2008, Vann et al., 2021). Without effective and affordable OMRI listed herbicides, organic growers are even more reliant on cultural practices like tillage for weed management (Peigné et al., 2007; Teasdale et al., 2007; McErlich, et al., 2013; Armengot et al. 2015). This repeated soil disturbance and inversion due to tillage contributes to soil erosion, nutrient loss, and reduced water-holding capacity (Uri et. al., 1998; Rawls et al., 2003; Stavi et al. 2011; Moebius-Clune et al., 2008; Wezel et al. 2014; Claassen et al., 2018). Flue-cured tobacco is plays a role in soil degradation throughout the Southeastern United States and in North Carolina in particular due to reliance on tillage, with estimates of between 33 and 40 tons ha^{-1} average annual soil loss (Wood & Worsham, 1986). Researchers have worked for decades to integrate conservation, or reduced tillage practices into the tobacco production systems. Conservation tillage is widely adopted in row-crop production to address these environmental issues, but flue-cured tobacco growers have been slow to adopt the practice due to concerns about poor weed control, potential for lodging, and restricted root growth (Fisher, 2004).

Conservation tillage is defined as a subcategory of reduced tillage that leaves a minimum of 30% of residue from the preceding crop after planting the subsequent crop (Conservation Technology Information Center, 2002). Reducing tillage and cover cropping has many on- and off-farm soil health benefits including increased rainwater infiltration, water-holding capacity, reduced erosion, reduced production costs (tillage fuel and labor), and reduced sediment, nutrient and pesticide runoff (Uri et. al., 1998; Dabney, 2001; Rawls et al., 2003; Stavi et al. 2011; Moebius-Clune et al., 2008; Wezel et al. 2014; Claassen et al., 2018). It is widely adopted in conventional field crop systems, although the Southeastern U.S. has lower implementation than other regions (Claassen et al., 2018). One strategy to minimize soil disturbance with conservation tillage is planting the cash crop directly into biomass residues of an overwintered cover crop using specialized planting equipment (Clark & SARE, 2007; Bergtold et al., 2020). These practices are less widely adopted in organic production due to the challenges of weed management and cover crop termination without OMRI-listed herbicides that are effective and affordable (Peigne et al., 2007; Teasdale et al., 2007; McErlich & Boydston, 2014; Armengot et al. 2015). In a conservation tillage system that involves an overwintered cover crop, the cover crop is typically terminated by roller-crimping prior to planting of the crop (Creamer & Dabney, 2002; Davis, 2010; Smith et al., 2011). The level of weed control achieved by roller-crimping cover crops is dependent on the weed population and correlated with the amount of cover crop biomass left in place to prevent weed seed germination (Davis et al., 2010; Smith et al., 2011; Mirskey et al., 2013; Reberg-Horton et al., 2013). In the Southeastern U.S., studies evaluating weed suppression by a cereal rye (*Secale cereal*) cover crop report the necessary amount of biomass ranged from 6,725 kg ha^{-1} to 8,967 kg ha^{-1} with some levels of suppression at levels as low as 2,840 kg ha^{-1} (Reeves et al., 2005; Davis et al., 2010; Smith et al., 2011; Mirsky et al., 2013; Schonbeck & Morse, 2020).

The opposing forces of reliance on intensive tillage and a need to preserve soil health have fueled numerous studies evaluating cover cropping and conservation tillage in tobacco production, with widely varying results (Britt & Slater, 1957; Hoyt, 1986; Wood & Worsham, 1986; Bathke et al., 1993; Collins & Hawks, 1993; Fisher, 2004; Gooden et al., 2008; Ritchey et al., 2012). In general, burley tobacco performs favorably in no- or reduced tillage systems compared with conventional tillage and the soil health benefits are significant (Hoyt, 1986; Hoyt, 2000; Pearce and Denton 2013; Zou et al., 2017). Flue-cured tobacco studies report more variable yield and quality results with challenges ranging from root growth impedance, lodging, weed interference, and problematic suckers. (Wood & Worsham, 1986; Flower; 2001; Fisher, 2004; Gooden et al., 2008). In order to integrate conservation tillage with flue-cure tobacco, a sufficiently thick cover crop mulch layer must be established to prevent weed emergence when the tobacco is young and unable to shade out weed competition, approximately between two and 6.5 weeks after transplant (Inman et al., 2018). An additional barrier to reducing tillage in flue-cured tobacco production is the belief that raised ridges or beds improve drainage, lighten soil texture and prevent standing water in the root zone, all of which are supported by research (Britt & Slater, 1957; Collins & Hawks, 1993; Vann et al, 2021). However, Bathke et al. (1993) found no differences in flue-cured tobacco yield between ridged or level ground production. Ultimately, the system continues to be evaluated because the environmental benefits are significant; conventional tillage can lead to up to 20 to 90 times greater soil loss compared to no tillage in North Carolina’s coastal plain tobacco growing region, and a reduction in sediment loss in tobacco fields of 82% with reduced tillage (Wood & Worsham, 1986; Hazel, 2008).

In this study, we compare the effects of conservation and conventional tillage and bedding in conjunction with a high biomass cereal rye grass cover crop on weed density and biomass, yield, quality, and cured leaf chemistry of flue-cured tobacco grown without herbicides for potential adoption by certified organic producers.

MATERIALS AND METHODS

Site and Experimental Design

Research studies were conducted in three environments: two locations over two years. In 2019 at the Cunningham Research Station (CRS) in Kinston, North Carolina on a Goldsboro loamy sand (Fine-loamy, siliceous, subactive, thermic Aquic Paleudults) and in 2020 on a Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults), and in 2020 at the Upper Coastal Plain Research Station (UCPRS) in Rocky Mount, North Carolina on a Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults). Organic production practices established by the National Organic Program were followed at CRS in 2019 and at UCPRS in 2020 according to the (USDA-AMS, 2000). In 2020 at CRS, the same practices were used aside from the use of imidacloprid treated transplants due to the unavailability of untreated plants.

Both locations were arranged as a split-plot randomized complete block design with four blocks. Field preparation (main-plot) was randomized to the block and consisted of either flat ground or raised bed treatments. Tillage (split-plot) was randomized within each field preparation treatment and included either conventional or conservation tillage. In conventional tillage treatments, an overwintered cover crop was mowed and then disked into the soil, in conservation tillage treatments the cover crop was terminated via roller-crimper and left in place prior to transplant. Each plot was 15 meters long and composed of four rows spaced at 1.12 m between rows with 0.61 m between plants and contained approximately 25 plants.

Field Preparation, Fertility Sources and Trial Management

Field preparation for cover crop establishment took place in October 2018 and 2019 with primary and secondary tillage and raised bed establishment. Cereal rye cv. Wren’s Abruzzi cover crop was broadcast over the entire trial area at a rate of 134.5 kg ha^{-1}. In 2018 no fertilizer was applied to the study, in 2019 the cover crop was fertilized at a rate of 33.5 kg ha^{-1} nitrogen (Allganic Sodium Nitrate 15-0-2, SQM Specialty Plant Nutrition, Atlanta, GA), approximately two months after seeding. In conventional tillage treatments, the cover crop was terminated by mowing in March and disking in April. In conservation tillage treatments, the cover crop was terminated using a single-row roller-crimper with adjustable rear rollers made to maintain raised beds (I & J Manufacturing, Gordonville, PA) to leave a layer of dead cover crop mulch in place.

The tobacco cultivar NC 196 (Goldleaf Seed Company, Hartsville, SC) was transplanted on 2 May 2019 and 28 April 2020 in CRS and 29 April 2020 in UCPRS using a two-row transplanter with no-till attachments (Fox Drive Transplanter; Checchi & Magli, Lehi, UT) adjusted for bedded production with 60 cm in-row spacing. In 2019, an approximately 20 cm slot was opened around the transplanted row caused by dragging of the cover crop mulch by the transplanter (Figure 3.1). In 2020, the transplanter was adjusted with additional weight and changing the factory-installed wavy coulters to straight coulters that effectively cut through the cover crop mulch, prevented dragging and reduced the bare soil around the transplanted row to 10 cm or less. Fertility was applied across the entire study evenly and consisted of a split application of 80 kg N ha^{-1} (Allganic Sodium Nitrate 15-0-2, SQM Specialty Plant Nutrition, Atlanta, GA) and sulfate of potash magnesia (K-MAG 0-0-22, Helena Agri-Enterprises, LLC, Colliersville, TN) at a rate of 150 kg K_2O ha^{-1} . No irrigation was applied in UCPRS, however in CRS the study received overhead irrigation at the station manager's discretion. Weeds in all treatments were hand pulled, no herbicide or cultivation was applied to any treatment.

Sample and data collection

Cereal rye cover crop biomass was measured by clipping one 0.5 m^2 square from each block for a total of four samples at the soil line approximately one week before termination. The samples were dried at 65°C until completely dry then weighed.

Soil resistance was measured in the early season (approximately one month post-transplanting) and in the late season at or shortly following harvest (where harvest occurred). Four measurements per plot were collected within the crop row using a digital penetrometer with an internal data logger than recorded cone resistance at 2.54 cm increments throughout the soil profile up to 45 cm depth or until maximum resistance occurred (FieldScout SC 900, 12.7 mm basal diameter, cone shaped tip, Spectrum Technologies, Aurora, IL). Measurements were divided into three soil depth categories (0-15, 15-30, and 30-45 cm) for analysis.

In-row and between-row weed emergence count (2019 and 2020) and biomass (2020 only) data were collected approximately one month post-transplanting. Weeds within two 1 m^2 rectangles per plot were clipped just above the soil line. Custom quadrats were constructed and used to collect in-row and between-row weed emergence data separately. In-row quadrats were sized to fit the tops of raised beds while between-row quadrats fit between the raised beds. After clipping, individual weeds were counted, and then all weed biomass was dried at 65°C for 72 hours prior to weighing. Monocot, dicot and *Amaranthaceae* spp. data were collected separately.

Leaf yield data were collected from all plants in the center two rows of each plot in Kinston 2019 and cured in forced-air bulk curing barns according to standard curing protocols. Cured leaves were weighed and graded using the USDA grading scale which assigns a numerical quality index value (1-100) associated with leaf maturity and ripeness (Bowman et al., 1988) and conventional price indices (Fisher et. al, 2021). Value was calculated using conventional pricing structures to allow for comparison with the majority of flue-cured tobacco produced in North Carolina. Stand counts were collected after final harvest for adjusting yield data on a per-plant basis. Yield data was not collected in 2020 due to standing water in the trial area throughout the growing season in both locations, a result of extreme rain events in the early and late growing season and placement of the studies in low areas of the field (Table 3.1 & Fig. 3.2).

Tobacco leaf tissue chemical concentrations were evaluated at harvest on composite cured leaf tissue when harvestable yield was available in 2019. Composite cured leaf samples were selected post-curing from a homogenized sample of tissue from all stalk positions and harvest dates. Leaf samples were ground to < 80-mesh after drying at 65°C for 72 hours. Leaf tissue chemical analysis was conducted by NCSU Tobacco Analytical Services lab. Total leaf NO_3^- concentration was analyzed using Macro-Kjeldahl method described by Nelson and Sommers (1973) and total alkaloid and reducing sugars were analyzed with a Perkin-Elmer Autosystem XL Gas Chromatograph system using the methods described by Davis (1976).

Statistical Analysis

All data were analyzed using the PROC GLIMMIX procedure in SAS v 9.4 (SAS Institute, Cary, NC). Residual plots and data distributions were examined to ensure the assumptions of ANOVA were met. Location and year were analyzed separately. Preparation (main-plot) and tillage (split-plot) were treated as fixed effects, whereas block and block by preparation were treated as random effects. Least squared mean separation with Tukey’s HSD adjustment at a significance of $p \leq 0.05$ was conducted when treatment was significant.

RESULTS AND DISCUSSION

Field Conditions

Extreme weather severely impacted the outcome of this study, diverging from the thirty year historic averages particularly in the 2020 environments. At CRS in 2019, total rainfall throughout the growing season was slightly less than the historic average with less than 50% of the typical rainfall in May (Table 3.1). Temperatures were also approximately in line with the historic averages with the exception of May when the average temperature exceeded the thirty year average by 2.6°C.

Average temperatures in 2020 were in line with historic averages in both locations with the exception of slightly low average temperatures in May and June at CRS. The remainder of the season was typical, as were all months at UCPRS. The study locations experienced both ends of the precipitation spectrum in 2020. May 2020 rainfall at CRS exceeded the thirty year average by 163% and at UCPRS by 133%. In June both locations received within 1 cm of the thirty year average. July 2020 ranked in the bottom third in precipitation across North Carolina over the last century (NOAA, 2021). CRS received just 40% of the average rainfall and UCPRS received 65% of the average in July 2020. August 2020 ranked among the wettest 10% for that month in a century in North Carolina, with nearly double the thirty year average rainfall at CRS and 250% the thirty year average at UCPRS due to multiple extreme rainfall events (Figure 3.2). The wide fluctuations in precipitation resulted in total cumulative rainfall (April-August) exceeding the thirty year average by 16.4 cm (129%) at CRS and 34.2 cm (164%) at UPCRS. Both 2020 trials were located in lower areas of the fields as depicted in Figure 3.2. The topography compounded the impacts of the extreme rainfall due to the resulting standing water in the trial areas for multiple periods throughout the growing season.

Climate experts predict North Carolina will experience extreme weather with increasing frequency in the future, including higher than historic rainfall, more regular extreme rainfall events and periodic moderate to severe drought similar to the weather patterns in 2020 (Kunkel et al., 2020).

Cover Crop Biomass

At CRS in 2019, cover crop biomass production was low, with cereal rye biomass production of 5,130 kg ha^{-1} (Figure 3.3). The level of cereal rye biomass reported to provide sufficient weed control in organic systems varies widely by region, weed pressure and crop. Cereal rye biomass residue of 8,967 kg ha^{-1} or greater is commonly referenced as the level of cereal rye cover crop biomass necessary to provide excellent weed suppression in organic systems in the Southeastern U. S. (Davis et al., 2010; Smith et al., 2011). Cover crop biomass production between 6,725 and 8,967 kg ha^{-1} provided sufficient weed suppression in organic soybean production in some North Carolina locations, but above 8,967 kg ha^{-1} was necessary to provide excellent control (Reberg-Horton et al., 2013). SARE publications report weed suppression with cereal rye biomass levels as low as 6,725 kg ha^{-1} while other research suggests that levels above 8,000 or 10,087.66 kg ha^{-1} are necessary for organic production (Smith et al., 2001; Mirsky et al, 2013; Schonbeck & Morse, 2020). Biomass production in the 2019 study falling well below all thresholds caused concern for the potential level of potential weed suppression in the study.

In 2020, both locations had much higher biomass production as a result of fall fertilizer application approximately one month after seeding the cover crop. The cover crop at CRS in 2020 produced 9,725 kg ha^{-1} cereal rye biomass, surpassing some thresholds but falling short of the level reported in other studies to achieve satisfactory weed suppression (Figure 3.3). Cereal rye cover crop biomass production of 10,175 kg ha^{-1} at UCPRS in 2020 surpassed all relevant thresholds reported in previous studies in the Southeast.

Soil resistance

Overall soil resistance results were variable, but generally insignificant (Tables 3.2, 3.3, and 3.4). Differences were mostly found in the shallowest soil depth measurements (0-15 cm) in both the early and late season measurements, the deeper segments often had insufficient data for analysis likely due to fragipan layer that prevented measurements in those segments in a number of plots. Greater soil resistance was observed in the flat ground treatments than in raised bed treatments in the late measurements at CRS in 2019 and 2020 (CRS 2019 $p < 0.0001$; CRS 2020 $p = 0.0109$; Table 3.2, 3.3). Flat ground treatments also had greater resistance than raised bed treatments in the middle soil depth measurement (15-30 cm) in the early measurement at UCPRS in 2020 ($p = 0.0033$; Table 3.4). In the shallowest early CRS 2020 measurement, an interaction of tillage × field preparation was observed, where flat ground conventional tillage treatments had higher soil resistance values than bedded conservation tillage and both preparations of conservation tillage ($p = 0.0026$; Table 3.3). Conventional tillage treatments resulted in greater resistance measurements than conservation tillage in the early measurement in the shallowest depth group at UCPRS in 2020 ($p = 0.0022$; Table 3.3).

Soil compaction associated with greater penetrometer resistance has been associated with mechanical root impedance and decreased tobacco root growth (Vepraskas & Miner, 1986; Collins & Hawks, 1993; Alameda et al., 2012; Ritchey et al, 2012). With inconsistent differences and no clear trend, a conclusion cannot be drawn from the soil resistance data in this study about the potential impact on tobacco root penetration and growth.

Weed density and biomass

Weed density and biomass were impacted by tillage system and in some cases, sampling location (in-row or between-row) and field preparation. There were significant first order interactions of either tillage × sample location or field preparation × sample location, but no second order interactions of tillage × sampling location × field preparation were significant in any environment ($p > 0.05$). At CRS in 2019, there was a significant first order interaction of tillage treatment × sampling location. Within the crop row, weed density in conservation tillage treatments were 18% lower than conventional tillage (55 plants m^{-2} vs 67 plants m^{-2}). Between rows, conservation tillage reduced weed density by 65% with 27 plants m^{-2} vs 78 plants m^{-2} ($p = 0.0136$; Table 3.5). Although the interaction was significant, the main effect of tillage is of interest in the context of comparison to previous studies. Weed density was 43% lower in conservation tillage treatments than in conventional treatments when between-row and in-row sampling locations were analyzed together, with an average of 41 plants m^{-2} in conservation tillage treatments compared with 72 plants m^{-2} in conventional tillage treatments. The same interaction (tillage × sampling location) was observed at CRS in 2020. Both sampling locations in conventional treatments were greater (186 plants m^{-2} in-row and 203 plants m^{-2} between row) than the conservation tillage treatments, and the in-row locations in conservation tillage treatments (70 plants m^{-2}) were greater than between-row samples (16 plants m^{-2}) in those treatments ($p = 0.0366$; Table 3.5). The overall difference in weed density between tillage treatments was excellent, with 78% reduction in weed density between conventional (194 plants

m^{-2}) and conservation tillage (42 plants m^{-2}). This level of weed control can be attributed to improved cover crop biomass in this environment, 9,725 kg ha^{-1} cereal rye biomass which exceeds some reported thresholds but falls short of others (Smith et al., 2001; Mirsky et al, 2013; Reberg-Horton et al., 2013; Schonbeck & Morse, 2020).

Weed biomass was collected in the 2020 environments. At CRS, differences were found between tillage treatments, sampling location and field preparation but no significant interactions among these variables were observed. There was a 76% reduction in biomass between the tillage treatments, 68% reduction between in-row and between row samples and a 40% reduction from bedded to flat ground treatments (tillage $p < 0.0001$; sample location $p < 0.0001$; field preparation $p = 0.0169$; Table 3.5). Although differences in sampling location and field preparation were not found in the weed density data both were different in the weed biomass data, indicating that weeds in these settings grew larger faster, or possibly germinated earlier, than in their respective alternate settings due to increased soil disturbance and exposure.

At UCPRS in 2020, similar trends in overall weed density were observed, with 69% lower weed density in conservation tillage than in conventional tillage ($p < 0.0001$; Table 3.5). An interaction between field preparation (bedded vs flat ground) and sampling location was observed in both weed density and biomass where the in-row sample in raised bed treatments was higher than all other treatments (density $p = 0.0253$; biomass $p = 0.0016$; Table 3.5).

The tillage × sampling location interaction was observed in *Amaranthus* sp. density at CRS 2019, but both conventional tillage sample locations had higher weed density than either sample location in conservation tillage treatments ($p = 0.0352$, Table 3.6). Within the crop row, weed density was reduced by 43% between tillage treatments. Given the relatively low cover crop biomass of 5,130 kg ha^{-1} in the 2019 study environment, these results compare favorably with other studies evaluating a rolled cover crop mulch without the use of herbicides. Studies throughout the Southeastern U.S. in vegetables, cotton, and soybean found weed density reduction between 26 and 56% with cover crop biomass ranging from 2,840 (26% reduction in weed density) up to 8,000 kg ha^{-1} (Reeves et al., 2005; Davis, 2010; Buchanan et al., 2016).

At CRS in 2020, *Amaranthus* sp. weed density and biomass followed a similar pattern to the overall weed analysis, with more dramatic disparity between the tillage treatments – 84% reduction in *Amaranthus* sp. density between conservation and conventional tillage and 82% reduction in *Amaranthus* sp. biomass ($p < 0.0001$; $p < 0.0001$; Table 3.6). There was also lower *Amaranthus* sp. biomass in between-row samples than in-row samples, but no interactions between tillage and sampling location were observed ($p = 0.0103$; Table 3.6). With some species in this genus able to grow to 2 m within a growing season and produce hundreds of thousands of seeds per plant, a production system that prevents germination could be an important piece of the weed management puzzle for both organic growers who operate without herbicides and conventional growers, who face the challenge of herbicide resistance with these specific weed species (Ward et al., 2013).

Amaranthus sp. weed populations were very low at UCPRS in 2020. *Amaranthus* sp. weed density was 96% lower in conservation tillage treatments than in conventional tillage treatments, this difference was driven by the almost complete lack of *Amaranthus* sp. presence in the conservation tillage treatments ($p = 0.0219$; Table 3.6). No differences were observed in *Amaranthus* sp. weed density in sample location or field preparation or in *Amaranthus* sp. biomass between tillage treatments, sample location or field preparation (Table 3.6)

In all three environments, weed density and biomass suppression by the cereal rye cover crop mulch met or exceeded the results found in similar settings (Reeves et al., 2005; Davis, 2010; Smith et al., 2011; Mirsky et al., 2013; Reberg-Horton et al., 2013; Buchanan et al., 2016; Schonbeck & Morse, 2020). Concern about weed competition in the crop row where the transplanter opened a slot of bare soil was warranted given the differences in weed density and biomass found. Adjusting the transplanter for the 2020 season reduced this issue but did not eliminate it. Greater weed density and biomass in raised bed treatments compared with the flat ground treatments may have many explanations, in the case of CRS and UCPRS 2020, it may be attributed to the frequent standing water in the study locations in the early and late seasons, and mild drought mid-season that created unfavorable growing conditions for tobacco and weeds alike.

Leaf Chemistry

There were no detectable differences in reducing sugar, total alkaloid or tissue nitrate concentrations in topping or cured post-harvest composite samples between tillage or field preparation treatments at CRS in 2019. Previous studies have shown inconsistent results correlating no-tillage with alkaloid concentrations depending on the year, indicating that there may be an association but it is not predictable and may be correlated with other confounding variables beyond tillage (Moschler et al., 1971). Total alkaloids ranged from 1.57% in conventional tillage treatments to 1.79 in conservation tillage treatments, and reducing sugars were 19.06% under conventional tillage and 19.45% under conservation tillage. These are both higher than the ideal reducing sugar to total alkaloid ratio of 9:1, the result of insufficient nitrogen fertility early in the season, which may result in tobacco with mild smoking quality (Flower, 1999). Growth in the 2020 environments was very uneven, and did not reach a suitable size for tissue sampling and analysis.

Yield, Quality, and Value

Yield: At CRS in 2019, cured leaf yield was 34.8% higher under conservation tillage practices than conventional treatments, with conservation tillage yielding 1,151.57 kg ha^{-1} compared with conventional tillage which yielded 855.13 kg ha^{-1} ($p = 0.0302$; Table 3.8). Yield of raised bed treatments exceeded flat ground treatments by 70.9%, 1,266.15 kg ha^{-1} compared with 740.57 kg ha^{-1} ($p = 0.0006$; Table 3.8). There was no impact from the interaction between tillage and field preparation treatments. In 2020, both locations of the trial suffered from the cool, wet early season and flooding several times throughout the season alternating with extremely dry periods (Table 3.1). Due to these conditions and the resulting mortality, neither location was harvested in 2020. The 2019 yield differences are inconsistent with most field studies comparing flue-cured tobacco production with reduced or no-tillage with conventional tillage, most likely because these studies rely on the full conventional tool box for weed management including highly effective herbicides. In an organic system without the use of herbicides, reliant on mechanical (hand) removal of weeds in both tillage systems, the cover crop mulch left intact by conservation tillage was highly effective at reducing weed emergence and biomass and therefore contributed to increased yields. Although some studies have found no differences in flue-cured tobacco yield based ridged or level ground production, most research is consistent with the results of this study and supports the use of raised beds or ridges in flue-cured tobacco production (Britt & Slater, 1957; Bathke et al., 1993, Collins & Hawks, 1993)

Quality Index: Crop quality was not affected by tillage system, conventional tillage and conservation tillage with cover crop mulch treatments at CRS 2019 received equivalent quality ratings (Table 3.8). Level ground treatments produced tobacco with slightly higher quality indices than raised bed treatments ($p = 0.0015$, Table 3.8). Tobacco crop quality is most frequently correlated with nitrogen availability and timing but is associated with a number of production practices (Henry et al., 2019). Tillage has not been shown to correlate with differences in crop quality (Vepraskas & Miner, 1987)

Value: Value per hectare is calculated using product of yield per hectare and typical price per weight for given quality rating, a reduction in either yield or crop quality leads to reduced crop value. Because crop quality indices were equivalent regardless of tillage system, crop value followed a similar pattern to yield with the value of conservation tillage treatments 35.4% higher than the value of conventional tillage treatments (Table 3.8). Flat treatments received a higher crop quality rating than bedded production on average, but because the bedded treatments yielded more, the crop value for bedded treatments was 62.2% higher than flat ground production.

CONCLUSION

Conservation tillage used in conjunction with a rolled cereal rye grass cover crop mulch was effective for weed emergence suppression especially between rows where the cover crop was undisturbed by planting. None of the levels of cover crop biomass in the three study environments completely prevented weed emergence, but control may improve with higher rye biomass. These results are consistent with previous research on conservation tillage with cover crop mulches in the southeastern U.S. For use in organic systems without herbicides, the conservation tillage approach would require hand labor to manage the weeds that do emerge, and the cover crop prevents utilizing cultivation if it is needed. In the study environment where harvest was possible, conservation tillage provided higher yields than conventional tillage, likely due to the weed control provided by the cover crop mulch.

Although weed suppression occurred in all three environments in which this study was conducted, environmental and topographical conditions causing standing water in the 2020 study locations resulted in total crop failures. As shown in other field studies on reduced tillage in flue-cured tobacco, the production system is vulnerable to less than ideal conditions. While tobacco does not tolerate saturated soils in any growing system, the inflexibility of this system makes crop rescue in unfavorable conditions significantly more difficult because in-season cultivation is not possible.

Although this study was conducted to evaluate the system for organic flue-cured tobacco, it may have value in conventional systems for integrated weed management. With the limited number of herbicides approved for use in tobacco, it is essential to conserve their efficacy by integrating alternative weed management approaches, especially if herbicide resistant biotypes of certain weed species are present in the field. Beyond weed management, reducing tillage by utilizing conservation techniques with cover crop mulches may have impacts on soil health measures like compaction and moisture conservation which would be beneficial in any farming system.

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Table 3.1 Cumulative rainfall and average temperature by month compared to the 30 year monthly cumulative average at Cunningham Research Station in Kinston, NC and Upper Coastal Plain Research Station in Rocky Mount, NC.

Location	**April**		**May**		**June**		**July**		**August**		**Total**
	Rainfall (cm)	℃	Rainfall (cm)	℃	Rainfall (cm)	℃	Rainfall (cm)	℃	Rainfall (cm)	℃	Rainfall (cm)
CRS 2019	8.1	17.8	4.3	24.0	13.3	24.7	12.0	27.2	11.7	25.3	49.4
CRS 2020	12.1	15.7	15.3	19.0	12.5	23.8	5.8	27.3	26.4	26.0	72.1
UCPRS 2020	14.7	15.1	12.0	18.4	22.0	23.6	8.5	27.1	30.2	25.4	87.4
CRS 30yr[a]	8.0	17.2	9.4	21.4	12.9	25.6	14.2	27.2	13.7	26.4	55.7
UCPRS 30yr	8.3	14.8	9.0	19.6	11.0	24.4	12.9	26.2	12.0	25.2	53.2

[a] 30-year averages calculated from 1981-2010 data taken from NCEI COOP stations located closest to respective ECONet stations

Table 3.2 Tillage and field preparation effect on soil resistance at the Cunningham Research Station in Kinston, NC in 2019.

Treatment	**CRS 2019**					
	Early[a]			**Late**[b]		
	0-15 cm	15-30 cm	30-45 cm	0-15 cm	15-30 cm	30-45 cm
	kPa					
Conventional Tillage	1018	2529	1485	1741	3546	2210
Conservation Tillage	982	2608	1561	1684	3566	2112
Bedded	948	2608	1492	1454 b[d]	3242	2235
Flat	1051	2451	1554	1971 a	3760	2087

[a] Approximately one month post-transplant

[b] At or shortly following harvest (where harvest occurred).

[c] Insufficient data for analysis.

[d] Means followed by the same letter within response are not different (Tukey's honest significant difference; α = 0.05) and represent the average of four replications and 4 treatment subsamples (n = 816 data points for each mean).

Table 3.3 Tillage, field preparation and tillage × preparation interaction effect on soil resistance at the Cunningham Research Station in Kinston, NC in 2020.

Treatment	**CRS 2020**					
	Early[a]			**Late**[b]		
	0-15 cm	15-30 cm	30-45 cm	0-15 cm	15-30 cm	30-45 cm
	——— kPa ———					
Conventional Tillage	1849	3795	3092	2999	4800	-[c]
Conservation Tillage	1523	3775	3529	3024	4532	-
Bedded	1375	3565	3462	2866 b[d]	4223	-
Flat	1997	4005	3159	3157 a	5110	-
Conv. Till × Bedded	1374 b	3413	3128	2861	4247	-
Conv. Till × Flat	2323 a	4178	3057	3137	5353	-
Cons. Till × Bedded	1375 b	3718	3796	2871	4198	-
Cons. Till × Flat	1761 b	3832	3262	3177	4866	-

[a] Approximately one month post-transplant

[b] At or shortly following harvest (where harvest occurred).

[c] Insufficient data for analysis.

[d] Means followed by the same letter within response are not different (Tukey's honest significant difference; α = 0.05) and represent the average of four replications and 4 treatment subsamples (n = 816 data points for each mean).

Table 3.4 Tillage and field preparation effect on soil resistance at the Upper Coastal Plain Research Station in Rocky Mount, NC in 2020.

Treatment	**UCPRS 2020**					
	Early[a]			**Late**[b]		
	0-15 cm	15-30 cm	30-45 cm	0-15 cm	15-30 cm	30-45 cm
	——— kPa ———					
Conventional Tillage	2307 a[c]	3617	2914	3672	4658	-[d]
Conservation Tillage	1927 b	3232	2984	3777	4979	-
Bedded	2184	3032 b	3132	3664	4719	-
Flat	2049	3817 a	2766	3784	4918	-

[a] Approximately one month post-transplant

[b] At or shortly following harvest (where harvest occurred).

[c] Means followed by the same letter within response are not different (Tukey’s honest significant difference; $\alpha = 0.05$) and represent the average of four replications and 4 treatment subsamples (n = 816 data points for each mean).

[d] Insufficient data for analysis.

Table 3.5 Tillage, sample location, field preparation and tillage × sample location interaction effect on weed density and biomass at the Cunningham Research Station in Kinston, NC in 2019 and 2020 and the Upper Coastal Plain Research Station in Rocky Mount, NC in 2020.

Treatment	**CRS 2019**		**CRS 2020**		**UCPRS 2020**	
	Weed density[a]	**Weed Biomass**[b]	**Weed density**	**Weed Biomass** [c]	**Weed density**	**Weed Biomass**
Conventional Tillage	72	*	194	84 a [d]	206 a	30
Conservation Tillage	41	*	42	20 b	64 b	20
In-row	61	*	128	79 a	152	32
Between-Row	52	*	109	25 b	117	18
Bedded	58	*	133	65 a	163	31
Flat	56	*	105	39 b	106	18
Conv. Till × In-row	67 a	*	187 a	125	227	42
Conv. Till × Between-Row	78 a	*	203 a	44	184	18
Cons. Till × In-row	55 a	*	70 b	34	76	21
Cons. Till × Between-Row	27 b	*	16 c	5	51	18
Bedded × In-row	55	*	153	102	200 a	46 a
Bedded × Between-Row	56	*	114	28	126 b	16 b
Flat × In-row	66	*	104	57	103 b	17 b
Flat × Between-Row	49	*	105	21	109 b	17 b

[a] Seedlings m^{-2} approximately one month post-transplant.

[b] Biomass data were not collected in 2019.

[c] Biomass in g m^{-2} with plants removed at the soil line and dried before weighing.

[d] Means followed by the same letter within response are not different (Tukey's honest significant difference; α = 0.05) and represent the average of four replications and 2 treatment subsamples (n = 8 data points for each mean).

Table 3.6 Tillage, sample location, field preparation and tillage × sample location interaction effect on *Amaranthus* sp. weed density and biomass at the Cunningham Research Station in Kinston, NC in 2019 and 2020 and the Upper Coastal Plain Research Station in Rocky Mount, NC in 2020.

Treatment	**CRS 2019**		**CRS 2020**		**UCPRS 2020**	
	***Amaranthus sp.* density**[a]	***Amaranthus sp.* Biomass**[b]	***Amaranthus sp.* density**	***Amaranthus sp.* Biomass**[c]	***Amaranthus sp.* density**	***Amaranthus sp.* Biomass**
Conventional Tillage	2.5	*	7.3 a [d]	10.6 a	1.4 a	0.2
Conservation Tillage	1.0	*	1.2 b	1.9 b	0.1 b	0.1
In-row	1.8	*	5.0	9.4 a	0.3	0.3
Between-Row	1.6	*	3.4	3.1 b	0.8	0.1
Bedded	1.6	*	4.8	8.1	0.6	0.1
Flat	1.9	*	3.7	4.3	0.8	0.2
Conv. Till × In-row	2.3 a	*	7.6	15.1	1.2	0.3
Conv. Till × Between-Row	2.6 a	*	6.9	6.1	1.6	0.1
Cons. Till × In-row	1.3 b	*	2.4	3.7	0.1	0.2
Cons. Till × Between-Row	0.70 b	*	0	0	0	0

[a] Seedlings m^{-2} approximately one month post-transplant.

[b] Biomass data were not collected in 2019.

[c] Biomass in g m^{-2} with plants removed at the soil line and dried before weighing.

[d] Means followed by the same letter within response are not different (Tukey's honest significant difference; α = 0.05) and represent the average of four replications and 2 treatment subsamples (n = 8 data points for each mean).

Table 3.7 Effect of mulch treatment on tobacco leaf yield, quality and value at Cunningham Research Station in Kinston, NC in 2019.

Treatment	**Yield (kg ha^{-1})**	**Quality Index**	**Value (USD ha^{-1})**
Conventional	855 b[a]	66 a	2303 b
Conservation	1152 a	65 a	3,117 a
Bedded	1266 a	64 b	3,353 a
Flat	741 b	67 a	2,067 b

[a] Means followed by the same letter within response are not different (Tukey's honest significant difference; $\alpha = 0.05$) and represent the average of four replications and approximately 20 subsamples (varied by location and treatment plot) (n = 80 data points for each mean).

Figure 3.1 Transplanted tobacco in cereal rye cover crop at Cunningham Research Station, Kinston, NC in April 2020 (a) and Upper Coastal Plain Research Station Rocky Mount, NC in April 2021 (b).

Figure 3.2 Standing water in study area at Upper Coastal Plain Research Station Rocky Mount, NC on May 20, 2021 (a) and Cunningham Research Station, Kinston, NC, June 17, 2021 (b)

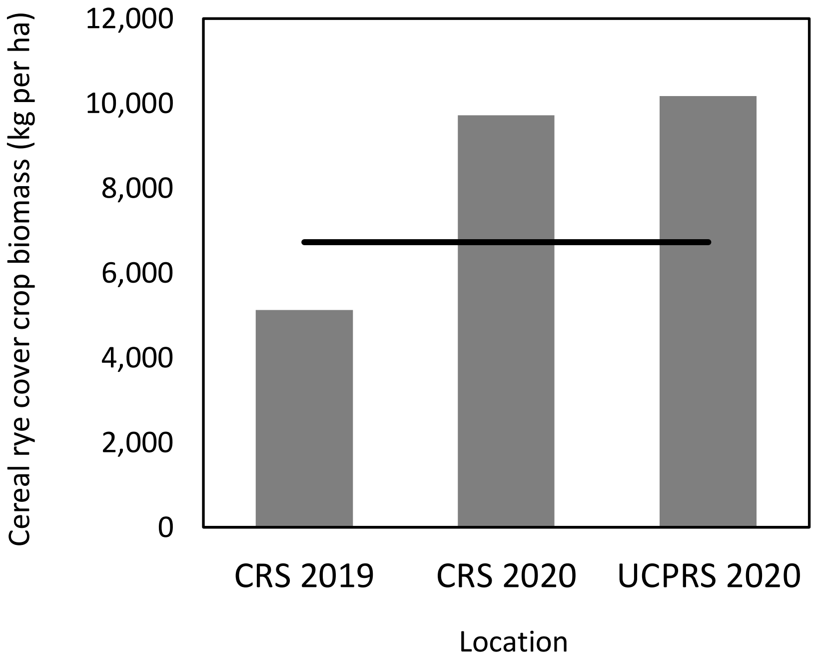

Figure 3.3 Cereal rye cover crop biomass approximately one week before termination at Cunningham Research Station, Kinston, NC in 2019 and 2020 and UCPRS in Rocky Mount, NC compared with minimum target biomass production for weed suppression. Biomass levels represent the average of four replications (n = 4 data points for each mean).