

**IMPACT OF PLANT POPULATION ON AGRONOMIC PERFORMANCE,
LABOR REQUIREMENTS, AND LEAF QUALITY IN BURLEY TOBACCO
(NICOTIANA TABACUM L.)**

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ABSTRACT

Increased labor costs and perceived yield declines have prompted burley tobacco (*Nicotiana tabacum* L.) producers to reconsider conventional plant populations. This study evaluated the effects of three planting densities, including 11,532, 17,574, and 23,065 plants ha⁻¹, on agronomic performance, cured leaf yield, labor requirements, and leaf quality in three burley tobacco cultivars (TN90LC, KT204LC, and KT222LC). Field trials were conducted over two years at the University of Tennessee's Northeast Tennessee (NETREC) and Highland Rim (HRREC) AgResearch and Education Centers using a randomized complete block design with factorial arrangement. Key metrics assessed included plant height, leaf number, stem diameter, total yield, and USDA federal grade index, as well as labor requirements for harvest and stripping. Yield was significantly impacted by cultivar selection and plant population, with modern burley tobacco hybrids (KT204LC and KT222LC) performing better than the older cultivar, TN90LC. Results demonstrated that increasing plant population significantly improved total cured leaf yield without significantly impacting leaf quality. However, labor hours for harvest and stripping increased by 22–28% under the highest plant density. Despite improved yields, partial budget analysis revealed diminishing returns at the highest density due to the increased input costs, mostly associated with labor, resulting in negative changes in net profit. Conversely, reducing population density lowered input cost but also reduced yield and potential revenue. Under the production and market conditions of this study, the recommended population of 17,574 plants ha⁻¹ remains the most economically and agronomically sustainable choice for burley tobacco producers;

however, the increases in labor costs and decrease in labor supply could prompt tobacco producers to choose planting densities which fall between 11,532 and 17,574 plants ha⁻¹.

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CHAPTER ONE

INTRODUCTION

Nicotiana tabacum

Nicotiana is a genus of plant that originated in the western world where European colonists found indigenous peoples using *Nicotiana* for medicine and ritualistic ceremonies (Garner, 1951). The knowledge and demand for *Nicotiana* spread from the western world to Europe, and it is now produced on all continents capable of agricultural production. The introduction of *Nicotiana tabacum* in the colonial times shifted use from *Nicotiana rustica* in favor of the larger *N. tabacum*. This switch to *N. tabacum* led to vast commercial tobacco production and expanded export markets for the colonies (Garner, 1951). The expanded market allowed tobacco exports to reach 24,482,862 kg in 1753 (Jacobstein, 1907). Most of the tobacco produced commercially in the USA is a type (flue-cured, burley, and dark) of the *N. tabacum* species.

Throughout the history of tobacco production, farmers would keep seeds from their best plants to sow for the following crop. Additionally, mutations have occurred where seeds were collected and a type of tobacco (burley) was established. Formal tobacco breeding programs have made great progress in breeding tobacco varieties that incorporated better yield potential, disease resistance, harvestability, and to adhere to secondary alkaloid tolerances (Bailey & Richmond, 2025b; Pearce, Richmond, et al., 2025). One tobacco breeding program focused primarily on burley and dark tobacco was based in Tennessee and Kentucky, called the ‘Kentucky-Tennessee Tobacco Improvement Initiative’ (KTTII).

Kentucky-Tennessee Tobacco Improvement Initiative

The KTTII originated with tobacco breeder Dr. Bob Miller. The major goal of this initiative was to release tobacco varieties for producers throughout Tennessee and Kentucky that had improved yield potential and disease resistance to the most prominent diseases producers faced. The varieties were released with names beginning with the letters ‘KT’ representing Kentucky and Tennessee with numbers following representing the year the varieties were released. This initiative officially began in the year 2000, however the program was rooted in Dr. Bob Miller’s tenure at the University of Kentucky and University of Tennessee beginning in the early 1980s. The last variety associated with KTTII was released in 2022. After 2000, varieties released were hybrids with male sterility, meaning they are from the first generation of offspring from the parents and seed cannot be kept for the next season. The most prominent disease issue that the KTTII targeted was black shank disease caused by the pathogen *Phytophthora nicotianae* (Bailey & Richmond, 2025b; Pandey, 2023; Pearce, Richmond, et al., 2025). There are multiple races of black shank that are pathogens of tobacco (Miller, 2023), but recently tobacco breeding programs focused on race 1 due to the genetic resistance acquired to race 0 (Antonopoulos et al., 2010) and the shift to race 1 in commercial production areas (Miller, 2023).

Tobacco Production

In 2023, United States’ tobacco ranked sixth in global tobacco production producing 196,160 tons of unprocessed tobacco leaf following China, India, Brazil, and Indonesia and Zimbabwe, respectively (Food and Agriculture Organization of the United

Nations, 2025). Sixty-two years ago, the United States total tobacco production peaked with 1,171,899.5 tons of tobacco leaf production (USDA NASS). The number of tobacco farms in the USA has significantly decreased in the last forty years (USDA NASS). In Tennessee, there were over 36,000 farms growing tobacco on over 33,000 hectares in 1982 (USDA NASS). Tobacco farms at this time were subject to quotas from the US Federal Tobacco Program. In 2022, there were only 241 tobacco farms growing tobacco on approximately 5,000 ha in the state of Tennessee (USDA NASS, 2025). These results report a 85% decrease in the number of ha in tobacco production and a 99% decrease in the number of farms producing tobacco in the state of Tennessee from 1982 to 2022.

The average allotment size was 0.9 hectares per farm in 1982 (**Figure 1.1**). In 2022, the average number of ha per farm was 20.8 (**Figure 1.1**). Tennessee has experienced a large reduction in the number of tobacco farms; however, the number of ha managed per farm has increased. A trend was observed considering the number of farms and average production area per farm, where graph lines intersected between 2002 and 2007 (**Figure 1.1**). Even with significant reductions in the total production of tobacco in the US, mostly due to a decrease in consumer demand and changes in federal regulations supporting tobacco production, the production regions have remained similar (University of Kentucky Department of Agricultural Economics, 2024).

The federal government was an active participant in managing the supply and demand of tobacco in the United States. Burley tobacco was part of this federal program starting in 1933 (Willigen & Eastwood, 1998). The program established restrictions on how much land or tobacco one producer could grow. Up until 1970, quotas were set

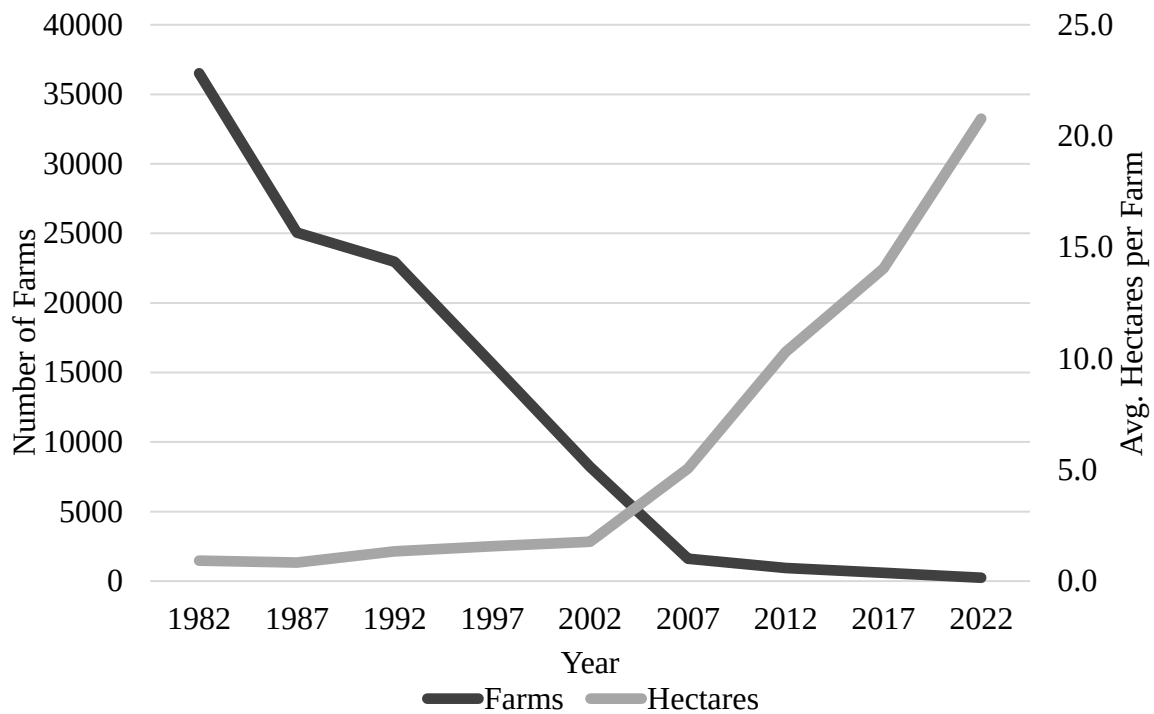


Figure 1.1 – relationship between the number of tobacco farms in Tennessee and the average number of ha per farm from 1982 to 2022 (40 years span) (USDA NASS: Census).

based on land allotment. After 1970, quotas were based on the amount of cured tobacco leaf produced. Under the Federal Tobacco Program, the majority of the farms relied on their family and local labor to produce the tobacco crop. As recently as 2002, the average number of ha per tobacco farm in Tennessee was less than 2 ha. Based on the 2022 census data, the average size of a tobacco operation is about 21 ha. The number of operations has continually decreased in the last 40 years, causing this shift in how many ha of tobacco are being managed per farm. This has led to a shift in the labor market for tobacco.

Tobacco, along with several other agricultural commodities, now relies heavily on the H-2A Visa Program (USDA). This program allows U.S. agricultural employers experiencing a shortage in domestic workers to hire foreign nonimmigrant workers to fill seasonal or temporary labor needs (Velandia et al., 2023). The majority of the temporary workers involved in H-2A Program are from Mexico and travel to the United States to work on farms for the growing season and harvest season (Wilson Center, 2022). This program has helped combat the shortage of domestic workers to produce tobacco crops. However, the cost of using the program have increased over time, due mainly to increases in the adverse effect wage rate, which is the minimum wage employers of H-2A workers must offer and pay to avoid potential effects on U.S. workers' conditions from hiring foreign nonimmigrant workers (Velandia et al., 2023). There are additional costs beyond wages that make the use of the program expensive, such as workers' housing and transportation (Velandia et al., 2023). In 2025, hired labor accounts for sixty percent of the variable costs in tobacco production (UT AREC, 2025), compared to about thirty

percent in 2001 (Mundy et al., 2001). The increase in labor cost has negatively impacted the profitability of burley tobacco. Growers have been trying to find more efficient production practices to maintain acceptable yields and leaf quality while minimizing labor requirements.

The U.S. cigarette sales have been declining at an increasing rate. Tobacco is currently produced in 18 states within the U.S. (USDA NASS, 2025). Approximately ninety percent of production occurs in the following four states: North Carolina (55%), Kentucky (21%), Virginia (7%), and Tennessee (6%). North Carolina and Virginia predominantly produce flue-cured tobacco while Tennessee and Kentucky produce burley (Type 31) and air- (Type 23) and fire-cured (Type 22) dark tobacco types. Burley and dark types of *Nicotiana tabacum* have traditionally been grown widely across the state of Tennessee. In 2022, burley and dark tobacco provided \$90,000,000 in farm gate income for the state (USDA NASS, 2025). Air-cured types of tobacco are mainly used in the production of combustible products like cigarettes and smokeless products like moist snuff.

Burley tobacco is classified as a light air-cured type of tobacco and is known for its upright growth and light color. The light-colored burley tobacco originated from a genetic mutation in Ohio around 1864. Tobacco, prior to 1864, was more similar to dark types of tobacco used for chewing (Willigen & Eastwood, 1998). Burley tobacco gained popularity in production for its characteristics and the ability to absorb flavorings used in the manufacturing of tobacco products (Palmer & Pearce, 1999). Burley is a major component in American-style cigarettes, making up roughly 20-30% of the blend,

depending on the manufacturer. Total production and contracted acreage of burley closely follow American blended cigarette consumption (University of Kentucky Department of Agricultural Economics, 2024). Burley and dark air-cured tobacco is cured in air-curing barns and is reliant upon the weather for relative humidity and temperature to drive the curing process.

Tennessee tobacco production has significantly changed in volume, proportion of each type grown, and geographical area of production in recent years. Historically, burley tobacco production accounted for the majority of Tennessee tobacco volume and was grown in approximately 75% of the counties, primarily in eastern and central regions. In recent years, burley production has declined to less than total dark tobacco production and has concentrated in the historical dark tobacco belt of the state with a total of 26 counties in 2022 (USDA NASS, 2025). Since 2015, dark tobacco production accounted for 65% of the total tobacco produced in Tennessee.

Markets for tobacco have experienced major shifts in demand. The increased consumer adoption of the next generation products, including nicotine pouches has caused decreases in dark tobacco production contracts because they are products which contain no tobacco leaf (Swedish Match, 2023). Burley demand continues to decrease as the demand for U.S. style cigarettes declines at a more rapid rate (University of Kentucky Department of Agricultural Economics, 2024). Competition with other international tobacco producing countries has negatively impacted the U.S. market due to the increasing quality of tobacco leaf from other tobacco-producing countries (Snell, 2003). Tobacco producers will need to find ways to remain efficient while meeting market

demands. With the recent decline in consumption of dark tobacco-containing products, contracted volumes have decreased leading to dark tobacco producers introducing burley tobacco to their farms.

Agronomic Practices of Tobacco

Field Preparation and Seedling Production

In contrast to row crops like maize and soybeans, tobacco is not directly seeded into the field for production. Tobacco is established in the field utilizing transplants that are produced for a period of 2 months prior to the targeted transplanting date (D. J. Fowlkes & D. Mundy, 2001; Pearce, Bailey, et al., 2025b). Traditionally, a sterile seed bed was created by burning plant material (brush, scrap lumber, etc.) over the area or fumigating, both of which are no longer used (Rhodes & Matthews, 1976). This practice would rid the seed bed of weeds and plant pathogens so tobacco seedlings could be better established. Bare-root plants were pulled from the seed bed immediately prior to transplanting. In the mid-1980s, a vegetable transplant producer introduced the float system, which soon became widely adopted for tobacco transplant production (Smith, 1999). Seeding tobacco in expanded polystyrene (EPS) trays in a float-bed greenhouse is now the most common method for producing transplants (Pearce, Bailey, et al., 2025b). There are numerous advantages associated with the transition to greenhouse float bed transplant production systems. One advantage to the float tray system is that plants can be pulled while the roots remain intact, which assists with reducing field transplant shock symptoms after transplanting (Smith, 1999). Greenhouse float-bed production of tobacco transplants promotes more uniformity of seed germination, plant growth, and more

uniform flowering near the topping stage of production (Ray, 1996). The float system utilizes EPS trays filled with soilless media and placed on a bed of water where nutrients and crop protection agents can be added to aid in healthy transplant production (Pearce, Bailey, et al., 2025b). Additionally, a major benefit of the float-bed system in a greenhouse is that the environment can be more readily controlled to optimize temperature, ventilation, growing media, and the nutrient solution in the float bed. Transplants are exposed to mechanical clipping of the uppermost 3 cm of vegetative growth to maximize airflow, promote uniform growth, and encourage stem and root growth (Pearce, Bailey, et al., 2025b; Smith, 1999). Float systems are slightly more expensive than traditional seedling production; however, the advantages have proven to outweigh the financial burden (Smith, 1999).

Tobacco production predominantly uses conventional or conservation tillage practices to prepare the field for transplanting. Most tobacco production occurs with a conventional tillage system due to limited agrochemicals for weed management and limited adapted equipment for successful no-till and conservation tillage practices (Palmer & Pearce, 1999; Pearce, Ritchey, et al., 2025b). Compared to other cropping systems, there are no genetically modified tobacco cultivars to resist herbicidal compounds that can be used in commercial production (USDA AMS, 2025). Fields are prepared with a primary tillage implement (like a chisel plow) followed by secondary tillage to enhance transplant root to soil contact. There are some benefits to tillage including alleviating layers of soil compaction, loosening the soil particles for easier transplanting, incorporating fertilizers and chemicals, and aiding in weed control

(Legleiter et al., 2025; Palmer & Pearce, 1999). Outside of tillage, there are a few pre-emergent herbicides that can be applied to the field prior to planting, with one herbicide option that can be applied after transplanting to aid in the control of weeds (Legleiter et al., 2025).

Soil fertilization and nutrient management are important components of producing any crop (Tang, 2025). Nitrogen is an important nutrient for tobacco production. In comparison to other types of tobacco, nitrogen requirements and subsequent recommendations are higher for burley and dark tobacco (Pearce, Ritchey, et al., 2025a). Current Extension recommendations are between 200-300 kgs of N hectare⁻¹ for recommended plant populations based on the previous crop and soil drainage classification (Palmer & Pearce, 1999; Pearce, Ritchey, et al., 2025a). Representative soil tests should be completed to determine recommended applications of remaining macro- and micronutrient fertilizer requirements as well as to determine if soil pH falls within acceptable ranges (Pearce, Ritchey, et al., 2025a). Using recommended rates and fertilizer sources are important to avoid issues associated with leaf quality and usability of the tobacco (Tso, 1999).

Transplanting and planting density

Transplanting is the act of placing tobacco seedlings in the field, commonly referred to as setting, at a desired plant and row spacing. Advancements have led to the invention of a mechanical transplanter (Willigen & Eastwood, 1998) that was introduced in the 1920's. Mechanical transplanters have evolved and improved from the earliest one-row wheel type transplanters to more modern two- to four-row carousel type transplanters

which have increased production efficiencies. Burley tobacco is commonly planted with a targeted population of 16,000 to 18,500 plants per ha (Pearce, Ritchey, et al., 2025b). Dark tobacco is grown with a wider plant spacing which results in a lower population density of around 11,000 to 13,500 plants per ha (Pearce, Ritchey, et al., 2025b). Row spacing will vary based on equipment availability and the row spacing of other necessary equipment utilized to produce tobacco, including equipment for cultivation and spraying. Change to planting population are adjusted primarily with plant spacing due to a fixed row spacing associated with various tobacco production activities like cultivation, spraying chemicals, and transplanting, (Link & Terrill, 1985). Burley tobacco is typically transplanted with row spacing ranging from 1.06-1.12 meters. Historically, plant spacing was 38 – 46 cm with other research trials looking at populations on a 30.5 cm plant spacing (D. J. Bosch, 1980; Rhodes & Matthews, 1976). Burley was historically grown on a 46 cm plant spacing; however, reports say 46-61 cm plant spacing was common in Kentucky, the major Burley Belt (Freeman, 1926). This spacing became the recommended spacing to achieve ideal populations per acre (Pearce, Ritchey, et al., 2025b).

Previous research investigated yield, plant growth characteristics, and economic considerations of increasing and decreasing tobacco plant populations. Several of these experiments examined the impact on input costs and primarily labor costs, of altering tobacco plant population. It is well documented that yield is positively related to planting density, with higher yields obtained at higher plant populations (Atkinson et al., 1971; Isaacs, 1992). Other research has concluded that yield is a function of the total number of

leaves per unit area (Elliot, 1970; Kittrell et al., 1975). In 1979, Peedin et al. (1979) found that yield is positively impacted by the number of plants and leaves per acre and concluded that labor requirement is reduced at lower plant populations (Peedin et al., 1979). Other work has considered differing fertilizer rates, plant population, and irrigation implementation and found that increased plant population increases yield and labor requirement (Atkinson et al., 1971). In 1985, a trial investigated the effect of increased plant spacing from 46 to 61 cm and found yield penalties associated with the 61 cm plant spacing on a per unit area basis. However, yield per plant and increased quality were observed with the 61 cm plant spacing (Link & Terrill, 1985). Furthermore, Link and Terrill suggested that a lower population could be profitable given the negative impact of increasing labor costs on profitability. Research completed in the early 1990s examined twenty different plant populations with differing combinations of row spacing and plant spacing ranging from 7,974 – 35,864 plants per ha (Isaacs, 1992). This work suggested that row spacing had less effect on yield than plant spacing, therefore concluding that within-row spacing is more impactful on burley tobacco yield (Isaacs, 1992). Adjusting row spacing is extremely limited based on existing farm equipment and considering current pricing structures for marketing burley leaf (UT AREC, 2025); therefore, producers are more likely to adjust plant spacing to achieve targeted plant population.

Differences in plant growth characteristics, such as stem diameter and leaf number, have been observed in previous studies evaluating different tobacco plant population densities. One study found that stem diameter was significantly decreased as

the number of plants per unit area increased (Isaacs, 1992). In the same study, the number of leaves tended to decrease when the planting population increased. Other research found no clear relationship between planting population and cured leaf quality or total value of burley tobacco (Atkinson et al., 1971; Isaacs, 1992). Decreased plant population was found to reduce labor requirement and result in heavier plants, heavier bodied tobacco, and potential for increased leaf quality (Isaacs, 1992; Link & Terrill, 1985).

All previous research was conducted using tobacco cultivars such as VA509 and TN86, which were released prior to 1990. Research investigating the impact of planting population on yield, crop quality, and profitability was primarily conducted before 1992 and has not been revisited after the introduction of the Low Converter (LC) protocol, where modern tobacco varieties have undergone more intense selection for chemical properties and yield improvements.

Practices During the Field Season

There are many considerations for tobacco production after the crop is transplanted in the field. Weed control is a large component of all agricultural cropping systems due to negative impacts such as yield loss and nutrient and resource competition. Weeds can reduce the yield of tobacco by up to 26% (Hauser & Miles, 1975). In tobacco production, climbing weeds can also cause physical damage to leaves during harvest and contaminate cured leaf bales that are taken to market (Legleiter et al., 2025; Palmer & Pearce, 1999). Weed control is also important as they can serve as a host for pests and diseases (Bailey, 2013). There are limited herbicides available for weed control in tobacco production (Legleiter et al., 2025); therefore, tobacco producers often also rely

on tillage and manual labor to manage weeds. Many of the herbicides used in tobacco production are applied and must be incorporated into the soil prior to tobacco being planted in the field, which does not provide full season control of weeds (Bailey, 2013). There is one herbicide available for post-transplant control of some grass weeds but it cannot be applied within 42 days of harvest of the tobacco (Legleiter et al., 2025).

Tobacco producers market cured leaf and, therefore, are not interested in seed production. This results in the removal of the apical meristem or inflorescence of the plant, commonly referred to as topping. Topping is performed to redirect nutrients from reproductive structures to maintain and expand vegetative leaves and typically includes removing the leaves that will not reach a marketable size (Bailey, Reed, et al., 2025). After topping, there is a loss of apical dominance that encourages axillary bud growth, commonly referred to as suckers (Thompson, 2001). Suckers emerge from leaf axils as a secondary attempt to produce a seed head to complete the reproductive growth cycle (Decker & Seltsmann, 1971). Each leaf axil can produce up to three suckers in normal commercial production but suckercides are applied after topping to prevent further production of suckers (Seltsmann & Kim, 1964). It is well documented that increased sucker control is positively related to crop performance for yield and leaf quality (Goins et al., 1993; Link et al., 1982; Sheets et al., 1994). During the Federal Tobacco Program, growers typically topped plants based on the size of the leaves present in the tip (4th) stalk position on the plant. After the end of the program, the size of tobacco operations increased and resulted in topping practices that have slightly changed to meet market

demand. Topping requires about 5-10 labor hours per acre to complete, depending on the axillary bud pressure and stage of growth (Mundy et al., 2001; Richmond et al., 2020).

Burley tobacco is stalk-harvested and placed on tobacco sticks during harvest for curing. Burley tobacco is manually cut at the base of the plant and immediately placed on a stick between 3 and 5 weeks after topping (Richmond, 2025). To allow for adequate air circulation during the cure, sticks generally have between 5-6 plants on each tobacco stick (D. Fowlkes & D. Mundy, 2001). Harvested burley will typically remain on the sticks in the field to wilt for 0-2 days before transport to a curing structure. There are advantages to allowing burley tobacco to field wilt prior to housing in a curing structure. This includes reduced potential damage or loss of leaves due to handling brittle tobacco, and loss of moisture from the plants is less strenuous on labor during housing in the curing structure (D. Fowlkes & D. Mundy, 2001). Burley tobacco sticks will be placed 25-30 cm apart in a curing structure for 8-10 weeks until the desired curing characteristics are achieved (Bailey & Richmond, 2025a). Total area of production needs to align with total barn space to have adequate curing facilities. Unlike dark-fired cured tobacco, it is improbable for the producer to successfully cure two crops of burley tobacco in the same barn in the same year (Bailey & Richmond, 2025a). Therefore, barn space is a necessary consideration for the total amount of burley tobacco that is produced and changes to plant population and area planted will alter the required space.

Preparing Burley Tobacco for the Market

After the tobacco has been cured, the leaves need to be removed from the stalks and sorted to industry standards based on stalk position. The removal of leaves from the

stalk is commonly referred to as stripping. During stripping, leaves will be separated into 3-4 separate stalk positions. These stalk positions flying (lower stalk), lug (lower mid-stalk), leaf (upper mid-stalk), and tip (upper stalk) and each stalk position has different physical and chemical characteristics. Stripping is one of the most laborious activities associated with burley tobacco production (Duncan & Wilhoit, 2014). There have been reductions in labor requirements for stripping burley tobacco, mostly through changes in market preparation, moving from hand-tied leaf to large bales (Duncan & Wilhoit, 2014).

Factors such as leaf body, color, length, and aroma contribute to the visual grading system and the leaf quality grade assigned is related to the pricing structure (Agricultural Marketing Service: Tobacco Division, 1990). During the Federal Tobacco Program, were composed of letters and numbers that corresponds to the characteristics listed previously, and a total of 115 different federal tobacco grades were available. The Federal Tobacco Program ended in 2004-2005. Currently, tobacco leaf is purchased directly from producers by companies that assign leaf quality grades based on specific company standards that correspond to price based on contractual arrangements.

Perceived Decline of Tobacco Yield

Declining burley tobacco yields have been a concern for producers for several years in the burley tobacco production belt in the U.S. Over the last 30 years, the average reported yield for burley tobacco have declined (USDA NASS, 2025). Burley tobacco yields ranged from 1,009-2,465 kg ha⁻¹, with reported yields peaking around 1970 (**Figure 1.2**). Since the 1970s, reported yields have declined from 2,465 to 1,824 kg ha⁻¹ in the 2010s. There are several additional considerations for this reported yield data from

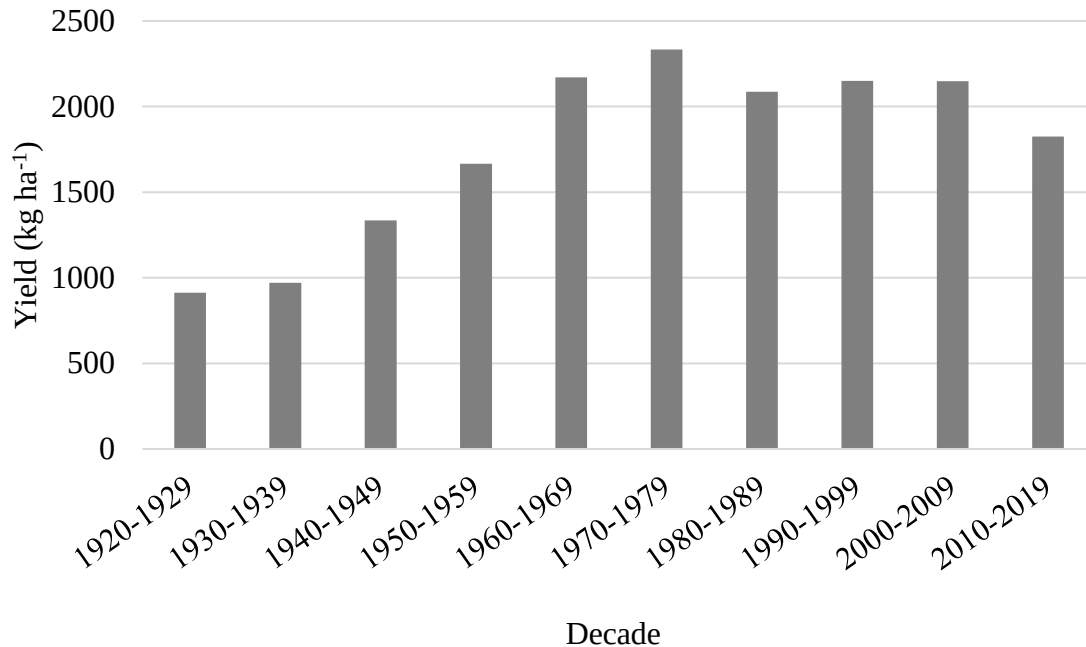
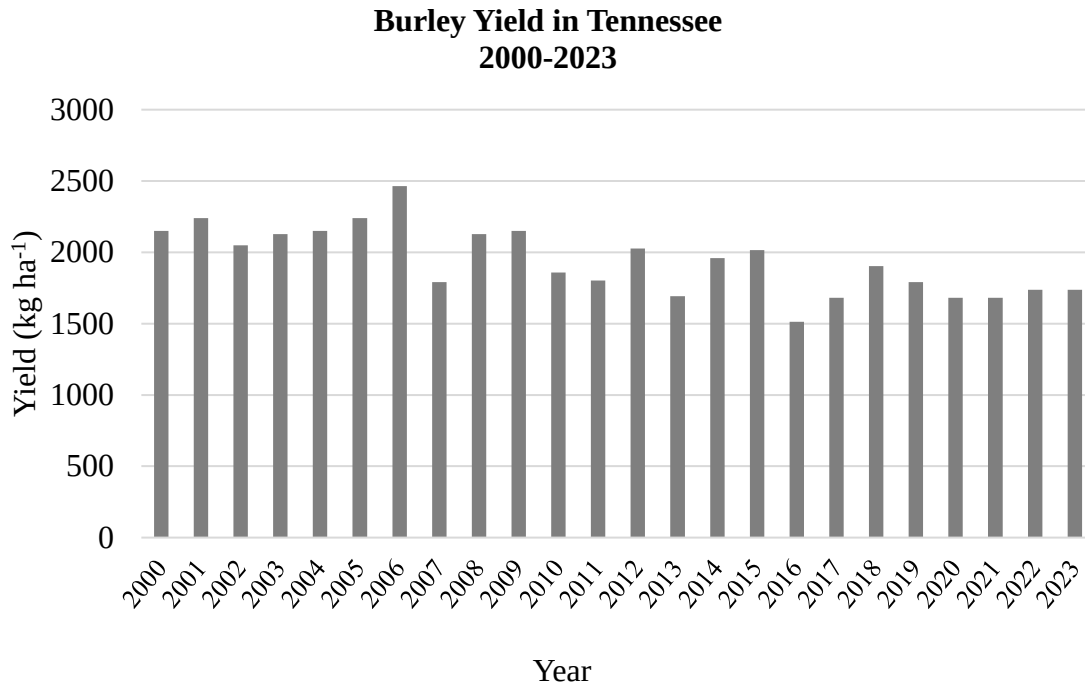


Figure 1.2 – Burley tobacco yield (kg ha⁻¹) in Tennessee in ten-year averages by decade (USDA NASS).

the United States Department of Agriculture National Agricultural Statistics Survey (USDA NASS). Firstly, quotas shifted from being restricted by area unit to weight of cured leaf harvested in the 1970s. During the 1980s, there was a change in the federal program allotment rules that allowed producers to have additional leases outside of county jurisdictions. This potentially could allow more acreage for one producer to manage and lead to changes in how intensely the crop is managed. The shift in the number of operations and average numbers of ha that producers manage also shifted in the early 2000s when another noticeable trend in decline occurred in the average reported yield of burley tobacco in Tennessee. A yield decline is apparent in the average reported yield per hectare of burley tobacco in Tennessee after 2006 (**Figure 1.3**).



Figures 1.3 – Average annual burley yield (kg ha⁻¹) in Tennessee from 2000 to 2023 (USDA NASS).

The reason behind the potential yield decline after 2006 is unknown. However, this yield reduction occurs soon after the end of the federal tobacco program, changes in the distribution of the tobacco production region, size of the tobacco operations, introduction of new technologies, and less predictable rainfall distribution in burley tobacco production. Tobacco varieties with resistance to common tobacco pathogens have been introduced to the market with known yield penalties; however, the benefit of innate resistance is very important for yield preservation (Chaplin, 1970). Climate data has not been analyzed within the regions of tobacco production about how it may affect the growing season of tobacco. Due to perceived yield decline and increased production costs, agronomic production practices need to be reevaluated to ensure long term profitability of burley tobacco producers.

Economics of Plant Population Density

Based on previous research, burley tobacco yield increases as the population of burley tobacco plants per hectare increases (Isaacs, 1992). Burley tobacco remains a labor-intensive crop, with about 60% of the variable costs accounting for labor at recommended planting populations (UT AREC, 2025). Labor requirement to produce a hectare of burley tobacco is positively related to planting population, due to the manual labor associated with handling additional plants. The current plant population recommendations (Pearce, Ritchey, et al., 2025b) for burley tobacco were generated in a way that yield and quality were maximized while minimizing labor inputs and meeting leaf characteristics' market demand. The goal of burley tobacco plant population research is to , minimizing labor needs while maximizing yield. When evaluating the economics of tobacco plant population densities, we need to consider potential changes in costs, including labor and plant costs, among other inputs, and potential changes in revenue, due mainly to yield. Additionally, there are considerations for space in available curing structures when increasing the tobacco plant population. Nonetheless, given the current tobacco market conditions, it is unlikely tobacco growers will consider investing in additional curing structures. Rather, if a producer opted for increased plant population, they may adjust their total production area to consider current curing structure capacity.

Summary of improvements for burley tobacco production

Significant improvements have been made to increase the efficiency of burley tobacco producers since the early 1970s (Duncan & Wilhoit, 2014). From a production standpoint, varieties have been improved over time with higher yield potential and

necessary disease resistant packages. The noteworthy improvements to reduce labor include the transition of plant beds to float-bed transplant production and adoption of large bales rather than hand tied tobacco for marketing tobacco. The total labor requirement reported in 1972 was 741 labor hours per hectare and has been reduced to about 371 with current production practices, which is a 50% reduction in total labor cost (Duncan & Wilhoit, 2014). However, even with the significant reduction in labor hours per hectare, nearly 60% of the total variable input costs are associated with labor in 2025 compared to 30% in the early 2000s. The price of labor per hour has increased to a point where more improvements to the efficiency of burley tobacco production are required to maintain profitability.

Objectives

Burley tobacco production has changed considerably over the long history of production in the traditional U.S. burley belt. The ongoing shift in labor and input costs provides an opportunity to re-evaluate plant population recommendations. Current recommendations for various production techniques should be evaluated to assess the impact on yield, crop quality, labor use, and economic feasibility. The objective of this research was to evaluate three planting populations (11,532, 17,574, 23,065) in three burley tobacco cultivars (TN90LC, KT204LC, and KT222LC) for impact on yield, crop throw, plant growth characteristics, leaf quality, and economic feasibility.

CHAPTER TWO

MATERIALS AND METHODS

Site Description and Trial Procedures

Research was conducted in 2023 and 2024 at the Northeast Tennessee AgResearch and Education Center (NETREC) near Greeneville and in 2024 at the Highland Rim AgResearch and Education Center (HRREC) near Springfield to evaluate the effect of plant spacing on growth parameters, yield, and leaf quality of burley tobacco varieties. The soil type at NETREC in 2023 was a fine, mixed, semiactive, thermic Rhodic Paleudalfs. The soil type was a fine-loamy, siliceous, semiactive, thermic Typic Paleudults at NETREC and a fine-silty, siliceous, semiactive, thermic Glossic Fragiudults at HRREC. The experimental design was a randomized complete block design (RCBD) with four replications and treatments were factorially arranged, including three plant populations and three burley tobacco varieties. All tobacco experiments were transplanted with a 107 cm row spacing. Plant spacing was 41 cm, 53 cm, and 81 cm to represent an average population of 23,065, 17,574, and 11,532 plants ha⁻¹, respectively. Plots were 4 rows wide by 12.5 m long. The treatments were imposed on the entire plot area, but all data were collected from the two center rows of each plot.

Plants of burley tobacco varieties ‘TN90LC’, ‘KT204LC’ and ‘KT222LC’ were produced in a greenhouse float-bed system with the use of recommended practices in both years of this study (Pearce, Bailey, et al., 2025a). The burley varieties selected for this study were developed by the KTTII over a period of 32 years, starting in 1990. To address rising tobacco producer concerns, this project included an older burley variety to

determine if newer varieties respond similarly to varying plant population. Tobacco seeds were direct seeded in 242-cell expanded polystyrene (EPS) trays on March 28, 2023, and March 22, 2024 at NETREC and March 11, 2024 at HRREC (**Table 2.1**). Test sites were prepared with the use of standard conventional tillage practices for each location in both years of this study. Tobacco plants were transplanted on June 5, 2023, and June 7, 2024 at NETREC and on May 21, 2024 at HRREC (**Table 2.1**). Applications of lime, potassium, and phosphorus were based on recommended rates for burley tobacco production from soil testing results (Pearce, Ritchey, et al., 2025a) (**Table 2.2**). Nitrogen was applied broadcast, preplant at a rate of 248 or 258 kg N ha⁻¹ using coated urea. There were no adjustments to nutrient management to compensate for increased or decreased plant population of tobacco plants, and all plots received a single fertilization rate. Tobacco was topped at 10-25% bloom and immediately treated with a tank mixture of maleic hydrazide and flumetralin for axillary bud control. All production practices followed current University of Tennessee Extension recommendations except for plant population (Bailey, Pearce, et al., 2025).

Plant height, harvestable leaf number, and stalk diameter were recorded from five random plants in the center two rows of each plot. Plant height measurements were taken from the ground to the node of the top-most leaf on the stalk and were taken within 2 weeks prior to harvest. Harvestable leaves were counted approximately one week prior to harvest to determine the final leaf number. The stem diameter of harvested plants was measured 3 cm above the visible soil line using a Husky digital caliper.

Table 2.1 – Important dates for the different stages of production for the Burley Plant Population experiments.

Location ^a	Year	Production Stage			
		Seeding	Transplanting	Harvest	Stripping
NETREC	2023	28-Mar	5-Jun	5-Sep	15-Nov
NETREC	2024	22-Mar	7-Jun	19-Sep	13-Dec
HRREC	2024	11-Mar	21-May	10-Sep	16-Jan

^a NETREC = Northeast Tennessee AgResearch and Education Center; HRREC = Highland Rim AgResearch and Education Center

Table 2.2 – Soil nutrient management for the Burley Plant Population experiments.

Location ^a	Year	Soil Nutrient Management			Source(s)
		N	P	K	
		----- kg ha ⁻¹ -----			
NETREC	2023	248	202	303	9-18-27 45-0-0
NETREC	2024	248	202	303	9-18-27 45-0-0
HRREC	2024	258	101	336	46-0-0 18-46-0 0-0-50

^a NETREC = Northeast Tennessee Research and Education Center near Greeneville, TN; HRREC = Highland Rim Research and Education Center near Springfield, TN

All plants from the center 2 rows, except the border plants, of each plot were stalk-harvested on September 5, 2023 (92 days after transplanting (DAT)) and September 19, 2024 (104 DAT) at NETREC and on September 10, 2024 (112 DAT) at HRREC. During harvest, 5 to 6 plants were placed on each stick and placed in an air-curing barn, and recommended practices were used to obtain leaf characteristics for market (Bailey & Richmond, 2025a). After curing, the tobacco leaves were removed (stripping) from the stalk and placed into 4 stalk positions consisting of flying (X), lug (C), leaf (B), and tip (T) and weighed to calculate yield per ha. Plots were stripped on November 15, 2023 (10 weeks after harvest (WAH)) and December 13, 2024 (12 WAH) at NETREC and on January 16, 2025 (18 WAH) at HRREC. Tobacco was graded according to U.S. Department of Agriculture (USDA) standards for burley tobacco (Agricultural Marketing Service: Tobacco Division, 1990) and grades were assigned an index value between 1 and 100 (Bowman et al., 1989). Grade index data are a weighted average of the grade across stalk positions and the yield proportion of each stalk position contributing to the total yield. Alkaloid and tobacco-specific nitrosamine (TSNA) samples consisted of 20 cured leaves collected from the fourth leaf position from the top of 20 plants in each plot. The samples were air-dried and ground to pass through a 1-mm screen. Samples were analyzed by Altria Client Services using gas chromatograph and mass spectroscopy methods (GCMS). Tobacco-specific nitrosamines (TSNAs) are presented as total TSNA in micrograms per gram, which is the sum of all individual TSNAs (NNN, NAT, NAB, and NNK).

Labor

The change in labor requirements when adjusting plant population was of interest in this experiment. Due to financial and logistical constraints, data were only collected on harvest and stripping procedures for two of the three site years. To determine labor-hours per ha, the amount of time to harvest and strip each plot was recorded. The two experimental locations (NETREC and HRREC) use different harvesting methods and labor sources (i.e., domestic and H-2A workers). At NETREC, domestic workers were used, and a two-man harvest crew, where one person cuts the plants (cutting) while the other person places the plant on the tobacco stick (spearing). To maintain consistency across the trials, the recorded time for harvest began when the first plant was cut in the plot and stopped when the last plant of the plot was placed on the tobacco stick. HRREC utilizes H-2A workers. Harvest at HRREC involves two phases, where a person cuts all of the plants and places the tobacco in piles of six plants. Then, the same person reentered the plot to place all plants on sticks. Cutting and spearing times per plot were combined to calculate the total harvest time. Data were not collected for labor hours to load tobacco sticks onto scaffold wagons or to house the tobacco in curing facilities. Each experimental site used one worker (HRREC) or one harvest team (NETREC) per blocked replicate to ensure that all workers experienced all treatments included in this experiment. Labor hours associated with removing the cured leaf from the stalk (stripping) were collected at NETREC in 2023 and 2024. Stripping labor data was not collected at HRREC in 2024. At NETREC, four workers strip tobacco with each worker responsible for removing the leaves of a designated grade (flying, lug, leaf, and tip). Labor hour data

collection began when the first worker removed the first leaf from the first stalk of the plot. The timer was stopped when the last leaf was pulled from the last stalk of the plot. Data beyond the act of leaf removal was not collected, including the baling of tobacco leaves or removal of the tobacco stalks.

Data Analysis

Data were analyzed using Statistical Analysis Software version 9.4 (*SAS Institute Inc.*). All data were subjected to analysis of variance (ANOVA) using the generalized linear mixed model procedure (GLIMMIX). Means of significant effects were separated using the LS-means multiple comparison procedure at a significance level of $\alpha = 0.10$. Plant density and variety were considered fixed effects while environment and replication were considered random effects. The site years which were considered as 3 environments are as follows: 1=NETREC, 2023; 2=NETREC, 2024; 3=HRREC, 2024.

Partial Budget Analysis

A partial budget analysis is used to evaluate marginal changes in costs and revenue associated with the use of different tobacco plant population densities (Kay & Edwards, 1999). This approach will allow us to determine the marginal changes in profits (per ha), due to changes in plant population densities. We compared marginal changes in costs and revenues associated with increasing or decreasing plant population compared to the recommended plant population for burley tobacco, which is approximately 17,574 plants per hectare (**Table 2.3 & 2.4**).

Table 2.3 - Components of a partial budget comparing the net changes in profits associated with increasing burley plant population to 23,065 plants per hectare

Additional Costs (AC)	Additional Revenue (AR)
Transplants	Potential tobacco yield Increase
Hired Labor	
Trucking/Hauling Costs	
Reduced Revenue (RR)	Reduced Costs (RC)
No reductions in revenue	No reductions in cost
A.Total AC and RR	B.Total AR and RC
Net Change (B - A)	

Table 2.4 - Components of a partial budget comparing the net changes in profits associated with decreasing burley plant population to 11,532 plants per hectare.

Additional Costs (AC)	Additional Revenue (AR)
No additional costs	No additional revenue
Reduced Revenue (RR)	Reduced Costs (RC)
Potential tobacco Yield reduction	Transplants
	Labor
	Trucking/Hauling Costs
A.Total AC and RR	B.Total AR and RC
Net Change (B-A)	

Profit is defined as gross revenue from production less total costs incurred:

$$\pi_T = R - C, \quad 1)$$

where π_T represents profits related to burley tobacco production; R represents revenue associated with burley tobacco production; C represents the total cost of burley tobacco production(e.g., fertilizer, labor, gas, equipment, repair, and maintenance).

Revenue for a burley tobacco operation using the recommended plant population for burley tobacco could be described as:

$$R_{RTP} = (p \times yield_{RTP}) \quad 2)$$

Revenue for a higher than the recommended burley tobacco plant population could be described as:

$$R_{HTP} = (p \times yield_{HTP}), \quad 3)$$

where p represents the price of burley tobacco, $yield_{RTP}$ and $yield_{HTP}$ are tobacco yields when using the recommended and higher population densities, respectively. Changes in revenue, due to the increase in plant population could be represented as:

$$\Delta R = \Delta p \times (\Delta yield) \quad 4)$$

where $\Delta yield$ is just the differences between $yield_{RTP}$ and $yield_{HTP}$, and Δp are potential changes in price p , or potential price discounts associated with changes in crop

quality. In this study, we assume revenue changes are mainly associated with changes in yield with a constant price per unit of tobacco.

Changes in costs associated with transitioning from the recommended plant population to the higher plant population can be represented by:

$$\Delta Costs = Costs_{HTP} - Costs_{RTP} \quad 5)$$

The cost side of the budget is affected when transitioning from the recommended to the higher plant population, as there are additional labor requirements for production activities, including harvesting, as well as additional seedling costs.

The data used to inform this partial budget analysis was the one described above from the field trials above. We also used information from the 2025 Burley Tobacco Budgets developed by the University of Tennessee and University of Kentucky (UT AREC, 2025). This budget is informed by burley tobacco producers, agricultural input suppliers, and tobacco industry representatives across Tennessee and Kentucky.

The field trial included three plant populations: 1) the recommended burley plant spacing of 17,574 plants hectare⁻¹, 2) a reduced population density of 11,532 plants hectare⁻¹, and 3) an increased population density of 23,065 plants hectare⁻¹. The baseline scenario, or the plant population density we compared to the alternative plant density scenarios, was the 17,574 plants hectare⁻¹. Labor hours for harvest or stripping were not significantly affected by variety; therefore, we used the average yield over all three varieties and site years in the partial budget analysis to reduce analysis complexity. Labor hour requirements were averaged within a planting density over all locations and years of

this trial. Labor data were collected for two stages of burley tobacco production, harvesting and stripping, to examine how labor hours to complete these activities change when transitioning from a recommended burley tobacco plant population to either a higher or lower population density per hectare.

Assumptions

There was no interaction between variety selection and plant population for total yield or leaf quality, therefore, data are pooled for partial budget analysis. The following assumptions were used to conduct the partial budget analyses (**Table 2.5**): (1) yield for each population density was estimated using average yields across three varieties of burley tobacco (TN90LC, KT204LC, and KT222LC), two locations (Greeneville and Springfield, TN), and two years (2023 and 2024); (2) average price per kilogram of burley tobacco was estimated at \$5.51 USD; (3) estimated price of burley tobacco transplants was \$60.00 USD per 1000 plants; (4) burley tobacco was planted with a 107 cm row spacing; (5) trucking and hauling costs at \$0.07 USD per kilogram of burley tobacco; (6) 372 labor hours are required to produce one hectare of burley tobacco at a population of 17,574 plants ha⁻¹; (7) labor data collected from field trials for harvesting and stripping of burley tobacco, we estimated a 20.5% decrease and 31% increase in labor for the lower and higher population, respectively, compared to the recommended plant population; (8) an assumed hourly wage rate was estimated at \$19.00 USD .

Table 2.5 – Data, estimate, and source used in the partial budget analysis.

Data	Estimate	Source
Yield -Kilograms (kg.) of cured tobacco leaves per hectare	Baseline = X kg/hectare Higher density = X kg/hectare Lower density = X kg/hectare	Average of yield across all varieties and all trial locations
Price = Price per kg of cured tobacco leaves	\$5.51 / kg.	University of Tennessee/ University of Kentucky Burley Tobacco Budget
Transplants	\$60 per 1000 plants	University of Tennessee/ University of Kentucky Burley Tobacco Budget
Labor		
Cost of labor per hour	\$19.00 / hr ; include 2025 adever effect wage rate (\$15.87) and additional expenses associated with the use of the H-2A program (e.g., worker housing, transportation)	University of Tennessee/ University of Kentucky Burley Tobacco Budget
Labor Changes	~21% reduction in labor for reduced population, ~25% increase in labor for increased population	Average of labor inputs (harvesting and stripping) across all trial locations and all varieties
Additional Costs		
Trucking/hauling	\$0.07 /kg.	University of Tennessee/ University of Kentucky Burley Tobacco Budget

CHAPTER THREE

RESULTS AND DISCUSSION

Yield Components, Total Yield, and Leaf Quality

Data for yield components, total yield, and leaf quality were pooled over environment, as environment was treated as random. There was not a significant two-way interaction between variety selection and plant population for flying, leaf, and tip stalk positions, total yield, or leaf quality. There was a significant two-way interaction between variety selection and plant population for lug stalk position.

Yield component data are utilized to compare the various stalk positions that are used to categorize burley tobacco based on the location of the leaf on the stalk. These stalk positions are associated with specific assigned grades that dictate the potential for marketing price. There were no significant differences associated with variety for X or B stalk positions (**Table 3.1**). There was a range of 11.4 to 11.9% for X and 56.1 to 56.9% for B across all varieties included in this study. There was a significant main effect of variety on the T yield component ($P=0.0003$), where KT222LC produced 17.4% tips stalk position compared to 15.7% for TN90LC and KT204LC (**Table 3.1**). There was an interaction between variety and density in the C stalk position. When examining the effects that density had within the varieties, TN90LC yielded significantly more C stalk position leaves (18.0%) when planted at the lower planting density ($11,532 \text{ plants ha}^{-1}$) than compared to 15.2 and 15.0% when planted at the recommended and higher planting density, respectively (**Figure 3.1**). It is important to note that these yield components are

Table 3.1 - Yield components, total yield, and leaf quality grade index for varieties and plant populations at NETREC^a (2023 and 2024) and HRREC^b (2024)

Variety	X ^c -----	B ^d Percent (%) -----	T ^e -----	Yield kg ha ⁻¹	GI 0-100
TN90LC	11.4	56.9	15.7 B	2,997 B	56 A
KT204LC	11.6	56.4	15.7 B	3,274 A	52 B
KT222LC	11.9	56.1	17.4 A	3,368 A	53 B
SEM ^f	0.03	0.05	0.01	395.26	8.06
P-Value ^g	0.6068	0.4501	0.0003	<0.0001	0.0313

Density (plants ha ⁻¹)					
11,532	10.6 b	58.4 a	14.4 c	2,842 c	56 a
17,574	11.8 a	56.7 b	16.4 b	3,252 b	54 ab
23,065	12.5 a	54.3 c	18.0 a	3,545 a	52 b
SEM	0.03	0.05	0.01	395.26	8.06
P-Value	0.0032	<0.0001	<0.0001	<0.0001	0.0337

^a NETREC = Northeast Tennessee Research and Education Center near Greeneville, TN

^b HHREC = Highland Rim Research and Education Center near Springfield, TN

^c X = Flying stalk position

^d B = Leaf stalk position

^e T = Tip stalk position

^f SEM = Standard Error of Mean

^g Means within the same column followed by the same lowercase or uppercase letter are not significantly different according to the LS Means procedure at P=0.10.

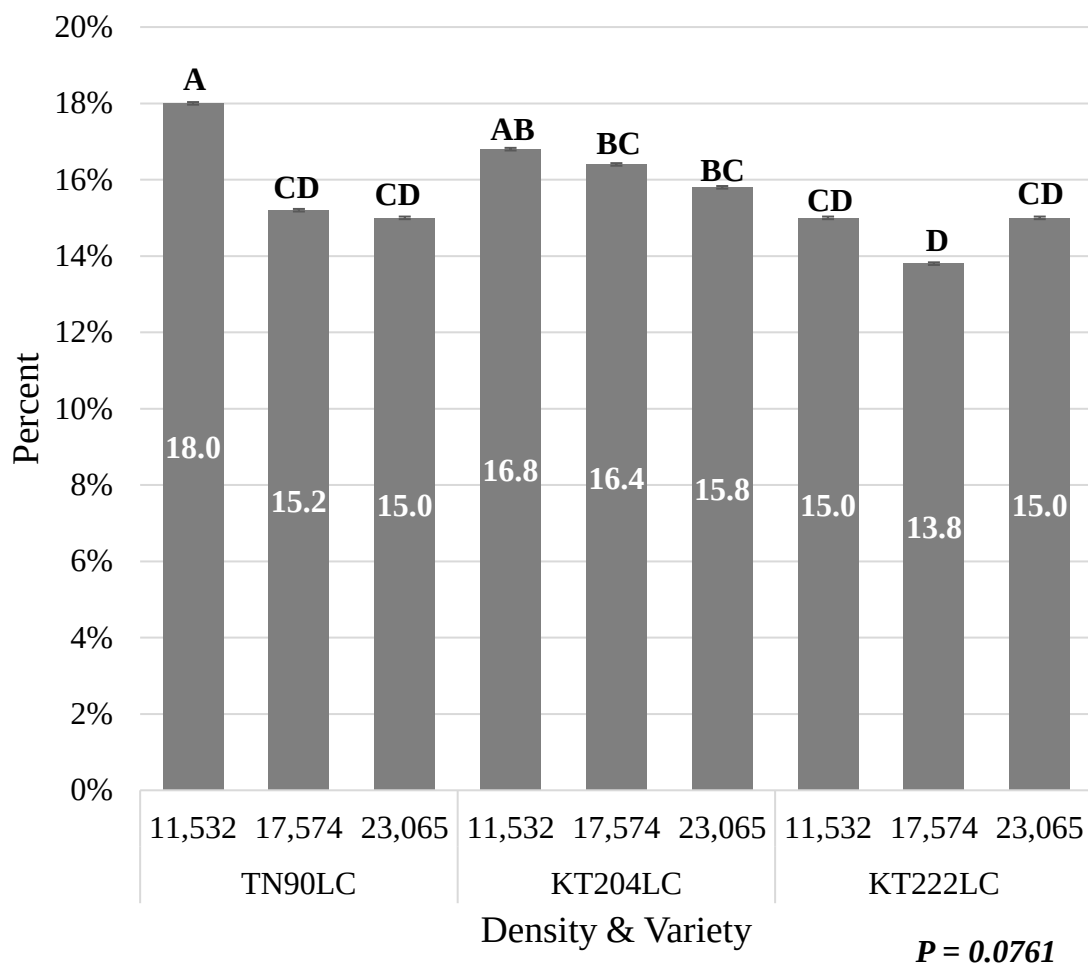


Figure 3.1 – Interaction of density and burley tobacco variety on the percent weight of the Lug (C) yield component.

based on the weight of the stalk position as selected by the farm worker based on visual breaks in leaf characteristics. This is an important designation as the market may assign an alternative grade to the stalk position, particularly T, based on some of the characteristics of the leaf. Therefore, the observed numerical difference, though statistically significant, likely doesn't impact the profitability of the variety comparisons.

There was a significant main effect of planting density on the percentage of X, B, and T (**Table 3.1**). The lower planting density (11,532 plants ha⁻¹) resulted in significantly less X stalk position (10.6%) compared to the recommended (11.8%) and the higher planting density (12.5%). There was a negative relationship in the B stalk position where the percentage decreased as the planting density increased. The lower planting density yielded 58.4% B stalk position compared to the higher planting density (54.3%). The T stalk position was positively related ($P < 0.0001$) to increasing plant density where the higher plant population resulted in 18.0% and 14.4% observed with the lower plant population. Evaluating the crop throw, or the distribution of leaves based on stalk position, is important for various reasons, including the price of leaves based on market preference. Typically, the most valuable burley tobacco stalk position is T. Therefore, the reduction in percentage of T yield components in the lower planting density may result in a less than ideal price when the leaf is delivered to the market. However, previous work suggests that there would have to be a larger premium for the price of tip leaves to persuade a producer to increase the growing population in order to achieve more tips per ha (D. J. Fowlkes & D. Mundy, 2001). These results suggest that planting density impacts the distribution of yield components more than the selection of

the burley cultivar due to the limited differences between the older cultivar (TN90LC) and newer hybrid burley cultivars. These results are consistent with previous research which achieved similar results using older varieties such, as Kentucky 14, VA509, TN86, and Burley 21 x Kentucky 10 (Atkinson et al., 1971; Bosch, 1980; Isaacs, 1992; Peedin et al., 1979).

There was a significant main effect ($P < 0.0001$) of variety and planting density on total yield. The newer hybrid burley varieties (KT204LC and KT222LC) produced significantly more total yield when compared to the older variety, TN90LC (**Table 3.1**). The variety TN90LC averaged $2,997 \text{ kg ha}^{-1}$ while the hybrid varieties averaged about $3,321 \text{ kg ha}^{-1}$ ($P < 0.0001$). As expected, increased plant density or higher plant populations resulted in significantly higher yields at each level included in this research. The average yield was 2,842, 3,252, and $3,545 \text{ kg ha}^{-1}$ for the lower, recommended, and higher planting densities, respectively. These results suggest successful efforts of the tobacco breeding program (KTTII) to improve yield potential with release of modern hybrid varieties while also incorporating a better disease resistance package.

The lack of interaction between variety and plant density suggests that all the varieties included in this research respond similarly to plant population changes. The higher plant density resulted in an additional 293 kg ha^{-1} of total yield compared to recommended plant populations, whereas the lower plant density resulted in a reduction of 410 kg ha^{-1} . These results align well with previous research that supports increased total yields from increased planting population (Atkinson et al., 1971; Bosch, 1980; Isaacs, 1992; Kittrell et al., 1975; Link & Terrill, 1985; Peedin et al., 1979). However,

tobacco production decisions must also include the cost of labor with the varying plant population as labor accounts for 60% of the total variable costs of production. The increased plant population, while resulting in significantly higher yield, also requires additional labor to perform all production practices throughout the growing season. It is noteworthy to mention that this research did not adjust nutrient management based on plant density and these results show the response to a recommended rate of fertilizer applied to the entire study.

Leaf quality is evaluated using an average grade index from assigned grades from the stalk positions and percent yield of corresponding stalk positions. The grade index values range from 0-100 where higher values are associated with higher quality. There was a significant main effect of variety ($P=0.0313$) on leaf quality where TN90LC had a significantly higher leaf quality with a grade index value of 56 compared to KT204LC and KT222LC which had grade index values of 52 and 53, respectively. This range in grade index values is expected to have limited impacts on the total value of the crop. Previous work fails to determine clear trends related to which variables impact leaf quality and is believed to be more impacted by growing and curing conditions. This research also found a trend of increasing leaf quality with decreasing planting density. The lower planting density resulted in a significantly higher grade index (56) compared to the higher planting density (52), where the recommended planting density (54) was an intermediate.

Agronomic Traits

Data for plant height, number of leaves, and stem diameter were pooled over environment, as environment was treated as random. There was not a significant two-way interaction between variety selection and plant population for yield components, total yield, or leaf quality.

Agronomic characteristics were of interest to determine if plant density and variety impacted growth parameters such as height, number of leaves, and stem diameter. There were no significant differences in the number of leaves or stem diameter when comparing the three burley tobacco varieties (**Table 3.2**). Average leaf number ranged from 19.3 to 19.6 total leaves remaining after topping. It was expected that limited differences would be observed for plant height and leaf number due to the act of manual topping to achieve a uniform height, rather than topping for tip leaf size. A significant main effect of variety was detected for plant height, where KT222LC exhibited slightly greater mean height (127 cm) than KT204LC (124 cm), while TN90LC did not differ significantly from either variety. However, the narrow range observed (124 to 127 cm) suggests these differences, although statistically significant, may not be biologically meaningful. Stem diameter at harvest ranged from 37 to 38 mm across all varieties, indicating limited varietal influence. This is somewhat of an interesting result, as TN90LC was expected to have a significantly smaller stem diameter due to the high harvestability rating with which this variety was released with.

There was no significant difference in plant height when comparing the various planting densities. There was a significant main effect of plant density on the number of

Table 3.2 - Mean plant height, number of leaves, and stem diameter for varieties and plant populations at NETREC^a (2023 and 2024) and HRREC^b(2024)

Variety	Plant Height (cm)	No. of Leaves (#)	Stem Diameter (mm)
TN90LC	125 AB	19.3	37
KT204LC	124 B	19.5	38
KT222LC	127 A	19.6	37
SEM ^c	9.29	1.49	2.63
P-Value ^d	0.0155	0.3295	0.1538

Density (plants ha ⁻¹)			
11,532	126	19.9 a	41 a
17,574	125	19.3 b	36 b
23,065	125	19.1 b	35 c
SEM	9.29	1.49	2.63
P-Value	0.5054	0.0002	<0.0001

^a NETREC = Northeast Tennessee Research and Education Center near Greeneville, TN

^b HHREC = Highland Rim Research and Education Center near Springfield, TN

^c SEM = Standard Error of Mean

^d Means within the same column followed by the same lowercase or uppercase letter are not significantly different according to the LS Means procedure at P=0.10.

leaves and stem diameter, however, plant height was not impacted (**Table 3.2**). The average plant height ranged from 125 to 126 cm across all planting densities. The lower plant density resulted in significantly more leaves per plant and increased stem diameter compared to recommended and higher plant densities. A similar trend was observed in previous research when comparing the number of leaves by planting density (Isaacs, 1992). The lower plant population resulted in about 5 to 6 mm thicker stem diameter, which is not surprising since less competition for resources is expected compared to increased plant populations. Ease of harvest, commonly referred to as harvestability, could be impacted by plants that have thicker stalks, but this was not determined from

survey data collected in 2024 (data not shown). The lack of significant differences for plant height combined with the significantly higher leaf number for the lower plant density suggests that internode length may have been slightly shorter compared to higher plant density treatments. Alternatively, higher populations may have induced lower leaf abortion. Nonetheless, significantly more leaves did not result in an increased yield for the lower plant population (**Table 3.1**).

Labor

Data for labor hours to cut and strip a ha of burley tobacco were pooled over environment, as environment was treated as random. There was not a significant two-way interaction between variety selection and plant population for labor hours required to cut and strip a ha of burley tobacco.

Determining how labor requirements change with varying plant populations is important to evaluate the impact of plant density on tobacco production labor needs. Tobacco production requires manual handling of each plant throughout most stages of production, and thus, labor needs need to be considered when altering the number of plants that will be handled per ha. Harvest labor hours were significantly impacted by plant population but not variety or the variety by plant population interaction.

As expected, the increased plant population required significantly more labor hours to harvest tobacco at each density included in this research. The average labor hours required to harvest were 23.76, 30.47, 39.09 hours ha⁻¹ for the lower, recommended, and higher planting densities, respectively (**Table 3.3**). These results demonstrate a clear trend of increasing labor requirements with higher burley tobacco

Table 3.3 - Mean of hours required to manually cut varieties at various plant densities at NETREC^a (2023 and 2024) and HRREC^b (2024)

	Harvest Time	
Variety	----- hr ha ⁻¹ -----	
TN90LC	31.45	
KT204LC	30.26	
KT222LC	31.61	
SEM ^c	3.52	
P-Value ^d	0.4514	
Density (plants ha ⁻¹)		
11,532	23.76	c
17,574	30.47	b
23,065	39.09	a
SEM	3.52	
P-Value	<0.0001	

^a NETREC = Northeast Tennessee Research and Education Center near Greeneville, TN

^b HRREC = Highland Rim Research and Education Center near Springfield, TN

^c SEM = Standard error of mean

^d Means within the same column followed by the same letter are not significantly different according to the LS Means procedure at P=0.10.

plant populations. Specifically, this study observed a 28% increase in labor hours required to harvest tobacco for each incremental increase in plant density, which reflects the added manual handling associated with increased plant populations.

Previous studies support these findings with Atkinson et al. (1971) documenting a positive relationship between labor cost and plant population across densities ranging from 16,549 to 33,098 plants ha⁻¹. While those trials did not include the lower density of 11,532 plants ha⁻¹ examined in the present study, the consistency of results across decades reinforces the robustness of this relationship. Isaacs (1992) further reported a near doubling of labor hours, from 313 to 706 hours ha⁻¹, as plant spacing narrowed from 91 to 31 cm within a constant row spacing of 107 cm. Together, these findings affirm that plant population remains a key driver of labor demand in burley tobacco systems.

Variety did not significantly influence the labor hours required to strip a ha of burley tobacco, with values ranging from 52.17 to 55.40 hours ha⁻¹ across the three varieties evaluated (**Table 3.4**). This was consistent with expectations, as no significant differences were observed in the number of leaves per plant among varieties (**Table 3.2**), and stripping time is largely dependent on the total number of plants and leaves. In contrast, planting density had a significant effect on labor requirements for stripping ($P < 0.0001$). Labor requirements to strip tobacco increased progressively with plant population with 42.56, 53.14, and 65.08 hours ha⁻¹ required for the lowest, recommended, and highest plant density, respectively (**Table 3.4**). These differences represent an approximate 23% increase in the required labor hours to strip burley tobacco for each increase in population. This trend reflects the greater number of plants and leaves that

Table 3.4 - Mean of hours required to remove tobacco leaves from stalks (strip) for each variety and plant population in 2023 and 2024 at NETREC^a.

Variety	Stripping Time	
	-----	hr ha ⁻¹ -----
TN90LC	52.17	
KT204LC	53.21	
KT222LC	55.40	
SEM ^b	5.65	
P-Value ^c	0.1277	
Density (plants ha ⁻¹)		
11532	42.56	c
17574	53.14	b
23065	65.08	a
SEM	5.65	
P-Value	<0.0001	

^a NETREC = Northeast Tennessee Research and Education Center near Greeneville, TN

^b SEM = Standard Error of Mean

^c Means within the same column followed by the same letter are not significantly different according to the LS Means procedure at P=0.10.

must be manually handled per unit area as population increases. These results are consistent with findings from previous studies conducted in two locations and two varieties, which have similarly reported increased labor requirements associated with higher planting densities in burley tobacco production (Atkinson et al., 1971; Isaacs, 1992).

Partial Budget Analysis

We estimated the net changes in profits when transitioning from the recommended plan population to a higher plant population and a lower plant population, based on the assumptions presented in Chapter Two. Because the analysis is based on the assumption discussed in Chapter Two, the results discussed here are hypothetical.

Although the results presented in this section are useful in assessing the factors that could potentially influence the economic feasibility of using various plant population densities, they do not represent actual changes in revenue and costs at the farm level. The net change in profit when transitioning from the recommended plant population to the higher population is estimated at about -\$467.45 USD per hectare, which implies a negative impact on profits associated with transitioning from 17,574 to 23,065 plants ha⁻¹ (**Table 3.5**). This result suggests that the additional revenue gained from increased yield does not compensate for the additional costs associated with increasing the population density.

The net change in profit when transitioning from the recommended plant population to the lower population is estimated at about -\$27.34 USD per hectare, which implies a negative impact on profits associated with transitioning from 17,574 to 11,532 plants ha⁻¹ (**Table 3.6**). This result suggests that the reduced expenses from decreased

Table 3.5 - Net changes in profit associated with increasing the number of burley tobacco plants from 17,574 to 23,065 plants hectare⁻¹

Additional Costs (AC) = \$2,078.59		Additional Revenue (AR) = \$1,611.14	
31% More Transplants	\$ 329.46	Additional Revenue	\$ 1,614.89
24.6% More Labor	\$ 1,736.86		
Trucking/Hauling	\$ 19.38		
Reduced Revenue (RR) = \$0.00		Reduced Costs (RC) = \$0.00	
No reduction in revenue		No reductions in cost	
A. Total AC and RR = \$ 2,085.70		B. Total AR and RC = \$ 1,614.89	
Net Change (B-A) = (\$ - 470.81) \$/ha			

Table 3.6 - Net changes in profit associated with decreasing the number of burley tobacco plants from 17,574 to 11,532 plant ha⁻¹

Additional Costs (AC) = \$0.00 No additional costs	Additional Revenue (AR) = \$0.00 No additional revenue
Reduced Revenue (RR) = \$2,259.74 Reduced Revenue \$ 2,259.74	Reduced Costs (RC) = \$2,232.40 34% Less Transplants \$ 362.52 26.1% Less Labor \$ 1,842.76 Trucking/hauling \$ 27.04
A. Total AC and RR = \$2,259.74	B. Total AR and RC = \$ 2,232.40
Net Change (B-A) = (\$ - 27.34) \$/ha	

transplant costs, labor, and hauling fees do not compensate for the loss of potential revenue associated with decreasing the population.

Increasing burley tobacco plant population from the recommended 17,574 plants ha⁻¹ to 23,065 plants ha⁻¹ resulted in higher cured leaf yield but ultimately led to a negative change in profits of \$470.81 ha⁻¹ (**Table 3.5**). While additional revenue from yield gains totaled \$1,614.89, it was outweighed by increased costs associated mostly with labor requirements. Labor requirement in this scenario accounted for \$1,736.86 of the \$2,085.70 in additional input costs.

Reducing burley tobacco plant population from the recommended 17,574 to 11,532 plants ha⁻¹ resulted in a negative change in profits of \$27.34 ha⁻¹ (**Table 3.6**). Although there were a cost savings associated with labor (\$1,842.76) and transplants (\$362.52), the cost savings were not sufficient to compensate for the total lost revenue from reduced total yield; however, savings make up 99% of costs that were included in the partial budget analysis. The reduction in variable input costs associated with the

reduced labor required to harvest and strip the lower planting density could also prove beneficial as labor shortages and constraints further impact the cost of labor. It is important to note that under current assumptions, a lower population density resulted in a lower negative impact on net profits compared to the higher population density scenario. These results suggest that the lower planting density have a higher chance of having a positive effect of the marginal costs difference when implementing a varying planting density.

CHAPTER FOUR

CONCLUSION

This study was conducted to evaluate the impact of plant population on yield, agronomic traits, labor requirements, and economic returns in modern burley tobacco varieties. Three burley tobacco varieties were included in the research, representing cultivars released over a 32-year span beginning in 1990. Across three environments (2023-NETREC, 2024-HRREC, and 2024-NETREC), plant population demonstrated a significant and consistent influence on the total cured leaf yield and labor requirements. While variety selection affected yield, favoring the newer hybrid cultivars, planting density emerged as the primary factor influencing total yield, labor requirements, and economic viability in burley tobacco production.

Increasing plant population to 23,065 plants ha⁻¹ significantly enhanced total yield, averaging 3,545 kg ha⁻¹, compared to 3,252 kg ha⁻¹ at the recommended density (17,574 plants ha⁻¹) and 2,842 kg ha⁻¹ at the reduced density (11,532 plants ha⁻¹). However, the yield gain was accompanied by an approximate 28.3% and 22.5% increase in labor required for harvest and stripping, respectively. Given that labor accounts for approximately 60% of total variable production costs, these added inputs led to a negative change in the net profits of \$470.81 ha⁻¹ at the highest plant population. While the lowest planting density experienced a significant yield penalty, the reduced labor demands and transplant costs led to a negative change in net profits of \$27.34 ha⁻¹ due mainly to reduced revenue.

Agronomic characteristics such as plant height, leaf number, and stem diameter were more strongly influenced by planting density than by variety. Lower plant populations produced more leaves per plant and larger stem diameters, potentially due to reduced competition. However, these changes did not translate into higher yields and higher gross revenue and are likely not biologically relevant. Leaf quality grade index was affected by variety where TN90LC had the highest quality rating which was 3-4 points higher than the KT tobacco hybrids. There was a trend where the lower planting density resulted in higher quality tobacco; however, the difference was 4 points.

These findings suggest that the changing labor market could influence producers to target lower planting densities to reduce labor costs. Increasing the planting density led to production inefficiency, as the additional labor costs outweighed the revenue gains from higher yields. In contrast, reducing the planting density resulted in lower potential yield and revenue. However, there were minimal economic impacts with the lower planting density when considering the associated production savings (labor, transplants, hauling).

As labor costs continue to rise, plant population will remain a critical management decision in burley tobacco production. Previous work in 1985 detected significant yield difference with a plant spacing change of 15 cm (Link & Terrill, 1985) while this research shows yield differences with plant spacing changes of up to 28 cm. This work, and previous work, would recommend that producers check for accuracy of transplant spacing to ensure that the individual operation is nearing optimum population. Future research should explore the integration of nutrient management and potential

labor-reducing strategies to enhance economic sustainability of burley tobacco production. Additionally, evaluating plant densities closer to current recommendations could yield more refined, fine-scale guidance for producers aiming to optimize performance under evolving production constraints.

In summary, increasing plant population improves yield but reduces marginal economic benefits due to disproportionate labor cost increases. Reducing plant population lowers labor inputs which may be more impactful for deciding the efficiency of tobacco production. Under the production and market conditions of this study, the recommended population of 17,574 plants ha⁻¹ remains an economically and agronomically sustainable choice for burley tobacco producers; however, the increases in labor costs and decrease in labor supply could prompt tobacco producers to choose planting densities which fall between 11,532 and 17,574 plants ha⁻¹.

One of the major limitations of the partial budget analysis presented in this study is the fact that we ignore potential labor cost changes associated with other production activities such as transplanting, topping, and stripping. We also ignore other potential changes in input costs, such as fertilizer costs at the various plant population levels. Furthermore, because the partial budget analysis is based on specific assumptions, future analysis should consider a sensitivity analysis to evaluate how changes in net profits change when changing, for example, labor costs and tobacco price assumptions. Finally, the high-density population scenario assumed that a grower already had a curing structure space capacity, which allowed him to consider this scenario. It is important to acknowledge that a higher-density population scenario will require a different investment

analysis if the grower does not have the curing structure capacity to consider a higher population density, given that he would have to invest in additional curing structures.

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VITA

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Sarah pursued a bachelor's degree in Crop and Soil Science with a minor in Geographic Information Science at Virginia Polytechnic Institute and State University (Virginia Tech) in 2020 which she completed in 2023. During her time at the Virginia Tech, she was employed by the Small Grains Breeding Program which exposed her to university research. Sarah also completed a Research Experience for Undergraduates (REU) at the University of Nebraska-Lincoln during the summer of 2022 where she completed her own research and presented it at a symposium held at the end of the internship.

Sarah continued her education at the University of Tennessee -Knoxville for her master's degree in Crop Science. During her time at the University of Tennessee, she has participated as a member of the Plant Sciences Graduate Student Association (PSGSA), departmental speaking competitions, national and international conferences, extension meetings with her advisor and several Field Day events in Tennessee and Kentucky.

Sarah plans to continue her education with a PhD at the University of Tennessee.