ABSTRACT

WHALEY, WILLIAM TYLER. Evaluation of Non-Tobacco Labeled Herbicides for Late Season Application. (Under the direction of Dr. Loren R. Fisher).

Recently, viable seed from various weed species have been found in tobacco exports, initiating great concern in foreign markets with a zero tolerance policy of flue-cured leaf shipments containing weed seed. It is believed that the majority of contamination occurs during mechanical harvest due to the presence of weed species. At present, the spectrum of herbicide options for tobacco is limited, specifically for post-transplanting application. The purpose of this research was to evaluate the use of non-tobacco labeled herbicides for late season application and determine the effects on crop injury, weed control, leaf yield, quality, and chemistry of flue-cured tobacco.

Field research was conducted at the Lower Coastal Plain Research Station (LCPRS) near Kinston, North Carolina and the Upper Coastal Plain Research Station (UCPRS) near Rocky Mount, North Carolina during 2014, 2015, and 2016. The experiment contained 17 total treatments evaluating eight different herbicides. The eight herbicides applied include *S*-metolachlor[4], sulfentrazone[2], trifloxysulfuron[5], fomesafen[6], glufosinate[7], mesotrione[8], linuron[9], and carfentrazone[10]. Each herbicide was applied before topping (BT) and after first harvest (AH) as a directed spray to the row middles when crop height was approximately 165 cm. The treatment containing only sulfentrazone and clomazone[3] applied pre-transplant (PRE-T) served as the control. Application rates were based upon current label recommendations established in other cropping systems. Visual ratings of percent crop injury and control of Palmer amaranth (*Amaranthus palmeri*) were recorded based upon a percentage scale from 0 to 100. Data were collected between one and two weeks after

treatment (WAT) to document percent injury of tobacco and percent control of Palmer amaranth.

Very low populations of Palmer amaranth were present at the LCPRS site, thus no significant difference in control was found among treatments over three years. Differences were found in BT applications of glufosinate and mesotrione in 2015. Significant injury was detected in 2016 when compared to the control from the applications of sulfentrazone BT, fomesafen BT, glufosinate BT, mesotrione BT, linuron BT, and carfentrazone BT. Despite crop injury from the above herbicides, yield, quality, value, and leaf chemistry were not affected in 2014 and 2016.

Differences were observed in 2015 for cured leaf yield, value, and reducing sugars. It is difficult to conclude that herbicide applications influenced leaf yield given limited crop injury and the absence of Palmer amaranth. However, the presence of soil-borne disease, primarily Black Shank (*Phytophthora nicotianae*) was confirmed late season in isolated locations within the experiment. As a result, it is likely that root and stalk infection affected yield potential and value within certain plots.

Greater Palmer amaranth density was present at each UCPRS site. As a result, differences in control were observed during 2015 but not in 2014 and 2016. Specifically, the application of sulfentrazone BT, linuron BT, glufosinate BT, and fomesafen BT resulted in 100, 100, 99, and 97% Palmer amaranth control respectively, indicating a difference when compared to the control (88%). Only trifloxysulfuron BT and linuron BT demonstrated greater Palmer amaranth control (90 and 100% respectively) compared to trifloxysulfuron AH and linuron AH (75 and 89% respectively).

Crop injury was observed from mesotrione BT and AH, glufosinate BT, and carfentrazone BT all three years while crop injury from glufosinate AH, carfentrazone AH, linuron BT and AH occurred in 2015 and 2016. Crop injury from sulfentrazone BT, fomesafen BT and AH occurred only in 2016. Leaf yield, quality, value, and chemistry were not affected by any of the herbicide applications.

Evaluation of Non-Tobacco Labeled Herbicides for Late Season Application

by
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DEDICATION

This thesis is dedicated to my mother, Paula Whaley. Thank you for the support you have given me throughout my educational career. Most importantly, I thank you for your unconditional love, unwavering faith in God, and the morals and values you instilled in me at an early age. I am forever grateful for everything you have done for me. You have truly been the best mother a son could ask for.

BIOGRAPHY

William Tyler Whaley was born on December 3rd, 1990 in Kinston, North Carolina. Having grown up on a tobacco farm, the value of a strong work ethic was instilled in him at an early age. In 2009, he graduated high school from Arendell Parrott Academy in Kinston, North Carolina and began pursuing a degree in Agriculture by attending North Carolina State University. He graduated from North Carolina State University in May of 2013 with a Bachelor's degree in Agricultural Science with minors in Crop Science and Agricultural Business Management. In the summer of 2013, he was admitted to graduate school at North Carolina State University to pursue a Master's of Science degree in Crop Science under the direction of Dr. Loren R. Fisher. Tyler is currently employed with the North Carolina Cooperative Extension Service as an Agriculture Extension Agent in Wayne County.

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INTRODUCTION

Tobacco (*Nicotiana tabacum* L.) is considered a crop with tremendous economic importance to certain countries worldwide. In 2015, approximately four billion kilograms of leaf were produced collectively across all tobacco growing regions, resulting in a global cigarette market value of US$698.5 billion (Brown, 2015; MacGuill, 2016). Within the United States, 69,201 ha of tobacco were harvested in North Carolina, resulting in 169 million kilogram of cured leaf produced (Crop Production Summary, 2015). Assuming an average price of US$4.11/kg of cured leaf, total value of tobacco produced in North Carolina is estimated to be US$695 million (Crop Values Summary, 2015).

Leaf Quality of U.S. Tobacco

As of 2015, only six percent of the global tobacco supply was produced in the United States (Brown, 2015). Nevertheless, U.S. tobacco producers still maintain a strategic market advantage in terms of leaf quality (Brown, 2015). The quality of leaf produced in the United States is unique compared to other tobacco producing regions. Multiple soil, climatic, and management factors determine leaf characteristics and properties favored by end users. Practices known to directly influence leaf quality include rate of nitrogen used and time of application, implementation of a sound sucker control program where MH residues are minimal, harvest rate and leaf ripeness, and leaf separation by stalk position (Fisher et. al., 2007). As a result, U.S. tobacco is preferred by manufacturers in product blends due to its cleanliness, style, flavor, and aroma.

Non-Tobacco Related Materials (NTRM)

Non-Tobacco Related Materials (NTRM) refers to all materials present that are not tobacco lamina and stem (CORESTA, 2005). Some materials classified as NTRM's include the following: soil particles, paper, string, metal fragments, tobacco stalks and suckers, plastics, foam materials, wood, grasses, weeds, oils and hessian fibers (CORESTA, 2005). If NTRM's are found in tobacco, domestic and international customers can and have rejected shipments of tobacco.

The prevention of NTRM's in the global tobacco supply is critical to maintaining leaf integrity. To guard against such contamination, current tobacco producers must be trained in Good Agricultural Practices (GAP) in order to market cured leaf in the United States. As part of the GAP initiative, growers are encouraged to implement practices at the farm level to prevent contamination of tobacco by foreign materials.

Furthermore, tobacco companies have drafted social responsibility policy guidelines or other similar documents to ensure operations meet legal and regulatory requirements while safeguarding social, economic, and environmental concerns (Corporate, 2016). Such guidelines are used to ensure that detailed objectives, ranging from agronomic, labor, and environmental practices, are satisfied (Corporate, 2016). These objectives are to be followed by all members of the supply chain in order to provide a consistent, quality product while maintaining compliance with regards to specific rules and regulations.

Discovery of Weed Seed in Tobacco

Tobacco producers strive to produce high quality leaf free of NTRM's that is desirable in domestic and foreign markets. However, in 2013, NTRM's in the form of weed seed were documented in processed leaf sourced from the U.S. These findings resulted in major concerns amongst export markets, specifically The Peoples Republic of China.

A Phytosanitary Certificate (PC) is required by the Chinese government for the introduction of flue-cured leaf (Phytosanitary, 2011). The ultimate purpose of certification is to attest that plants, plant products, or other regulated articles meet the phytosanitary requirements of importing countries and conform with the certifying statement (ISPM 12, 2016). More specifically, the certifying statement ensures that plant-related material has been inspected and/or tested according to appropriate official procedures and are considered to be free from quarantine pests specified by the importing contracting party (ISPM 12, 2016). If requirements are not satisfied, the National Plant Protection Organization (NPPO) for the importing country may take appropriate action if a certificate is deemed invalid or fraudulent (ISPM 12, 2016).

The Chinese agency responsible for the management and inspection of import and export commodities is known as the China Inspection and Quarantine Office (CIQ) (Ge, 2016). The CIQ further investigated weed seed contamination in flue-cured leaf by conducting grow out studies of weed seed found on processed leaf samples (Vann, 2014). The conclusions from these studies were twofold: 1.) weed seed remained viable regardless of leaf processing events and 2.) the identification of weed species was confirmed (Vann, 2014). Of the weed species documented, giant foxtail (*Setaria faberi*), large crabgrass (*Digitaria sanguinalis*), Palmer amaranth (*Amaranthus palmeri*), bahia grass (*Paspalum notatum*), goosegrass (*Eleusine indica*), and common ragweed (*Ambrosia artemisifolia*) are common in tobacco producing regions of the United States (Vann, 2014). At this time, no shipment of tobacco from the U.S. has been rejected by export markets due to presence of weed seed. However, the CIQ has the authority to reject shipment of U.S. tobacco if deemed necessary. Such action could jeopardize the future of the U.S. tobacco industry.

Comprehensive Approach to Weed Management in Tobacco

Because viable weed seed have been found in shipments of U.S. tobacco, producers must implement a comprehensive approach to weed management through the use of diverse practices at their disposal. It is imperative that this approach be used throughout the duration of the growing season to prevent seed production from problematic weeds in addition to reducing weed seed germination in future years. Despite advances in control technologies, weeds continue to be the most damaging of crop pests due to their ability to adapt in response to new management strategies (Sosnoskie et. al., 2006). In a flue-cured tobacco production system, the following practices encompass a total weed management program: crop rotation, cultivation, hand removal, early stalk and root destruction, and herbicides (Vann et. al., 2016).

Non-Herbicidal Weed Management Options

The use of crop rotation is common throughout tobacco growing regions. Crop rotations increase crop yields by improving soil conditions and reducing weed, insect, and disease populations (Roth, 1996). A well planned crop rotation system can also help producers avoid problems associated with conservation tillage, such as increased soil compaction, perennial weeds, plant diseases, and slow early season growth (Roth, 1996). In addition, enhancement of soil physical properties, efficient use of plant nutrients, and timely crop management can be achieved through a diversified crop rotation (Roth, 1996).

Tobacco is rotated with other crops primarily for disease management. The presence of a non-host crop aids in tobacco disease management by denying the causal agent a suitable plant on which it can feed and multiply for a long period of time (Collins and Hawks, 2013). In addition to disease suppression, tobacco can be used in a crop rotation to reduce weed populations. Due to tobacco's high crop value, growers can employ multiple options that are either too costly or too time consuming in the production of other agronomic crops (Fisher and Smith, 2003). Since many weed and crop species have similar phenology, their control options may be limited (Tingle and Chandler, 2004). By planting rotational crops, production practices can be adjusted to control select weed species (Tingle and Chandler, 2004).

Research has indicated that herbicide type and crop growth habit might effectively control weeds when used in a particular rotation (Derksen et. al., 1995). Additional studies have shown that after a three year rotation that included corn, johnsongrass and entireleaf morningglory control was more effective which resulted in increased crop yields (Tingle and Chandler, 2004). This suggests that crop selection and competition can have a direct influence on weed suppression.

Management of Palmer amaranth in tobacco production is critical due to its robust growth habit and ability to interfere with harvest. If Palmer amaranth reaches a height greater than tobacco, seed produced can fall onto tobacco leaves where the leaf surface can retain them during harvest, curing, and processing (Vann, 2014). Practices involving the use of herbicides, cultivation, and hand weeding can greatly reduce the presence of Palmer amaranth in tobacco. Research has demonstrated that management practices utilized in the production of flue-cured tobacco can greatly reduce Palmer amaranth density in subsequent agronomic crops. (Vann, 2015). Furthermore, conversations with tobacco producers, cooperative extension agents, and extension specialists across tobacco growing regions of the United States indicate lower Palmer amaranth populations in crops planted in succession with flue-cured tobacco (L. R. Fisher and B. M. Spivey, personnel communication, January 15, 2015).

Currently, tobacco growers utilize soil tillage practices prior to transplanting for soil conditioning and bed formation. Common tillage implements used to accomplish such task include: disk harrows, chisel plows, field conditioners, and bed shapers containing a ripper shank. Apart from soil conditioning and formation, tillage implements can be utilized for herbicide, insecticide, and soil fumigant applications, thereby justifying multiple field passes.

Implementation of cultural and mechanical practices affects weed population and seed production, and thus can delay the development of herbicide resistance by reducing the number of herbicide resistant alleles in the population (Beckie, 2006). Studies have been conducted to evaluate the use of deep tillage in flue-cured tobacco and its effect on Palmer amaranth suppression in a three year cropping rotation with other agronomic crops. Deep tillage reduced Palmer amaranth density in early season ratings when only clomazone was present in the herbicide program (Vann, 2015). At weed ratings later in the season (6 weeks after transplanting), the use of deep tillage did not reduce Palmer amaranth density, indicating that row ridging and post-transplanting cultivation might have re-exposed viable Palmer amaranth seed that had been previously buried by deep tillage (Vann, 2015). During years two and three, the effects of primary tillage on Palmer amaranth suppression in tobacco were not observed in cotton, also supporting the fact that row ridging and post-transplant cultivation in tobacco negated the benefits of deep tillage that have been reported in other agronomic crops (Vann, 2015). The conclusions reached in this study support the need for incorporation of multiple weed management strategies, such as the use of additional herbicides late season, in agronomic cropping systems.

Tobacco growers can also utilize tillage practices through the use of post-transplanting cultivation. Flue-cured tobacco is cultivated post-transplant for three primary reasons: 1.) promotion of a high row ridge to reduce incidence of drowning, nutrient leaching, and wind damage, 2.) loosen soil to assist in water penetration and aeration, and 3.) control weeds (Collins and Hawks, 2013). The buildup of a high row ridge supports a favorable soil environment for optimum tobacco growth and development. In addition, soil drainage is supported through the use of cultivation to protect roots sensitive to saturated soil and encourage rapid root growth and establishment (Collins and Hawks, 2013). With respect to weed control, cultivation is often used to disturb weed growth early season in hopes maintaining adequate weed control until canopy closure. Research suggests that reducing the number of in-season cultivations from three (normal number) to two only gave a slight reduction in yield, but reducing the number of cultivations to one gave a larger yield reduction (Collins and Hawks, 2013). Removing all cultivation events reduced leaf yield further, resulting in the lowest yield of any treatment even when herbicides were used to manage weeds (Collins and Hawks, 2013). Multiple cultivations benefit tobacco production beyond weed management and are therefore commonly employed regardless of weed pressure (Collins and Hawks, 2013).

Weed control in the form of hand removal is often not justified in many agronomic crops due to profit margins relative to tobacco. However, the economic value and current use of hand labor for other management practices in tobacco allow growers to justify this practice. Previous studies in tobacco have shown that, dependent upon herbicide selection and primary tillage method, hand labor costs can range from $US 0.38 ha^{-1} to $US 158.08 ha^{-1} (Vann, 2015). In combination with herbicides, hand removal of problematic weeds such as Palmer amaranth has contributed to seed bank reduction (Ward et. al., 2013). However, hand pulled Palmer amaranth that is left in the field can establish new roots and continue to produce seed (Sosnoskie et. al., 2012). Therefore, physical removal from the field site of larger plants is equally important as initial root growth disturbance. Due to Palmer amaranth's prolific seed production and herbicidal resistance capability, hand removal should occur prior to seed production to reduce seedbank populations and potential contamination of harvested product (Sosnoskie et. al., 2014; Vann, 2015).

Additional weed control practices employed in tobacco include after harvest tobacco stalk and root destruction that also disrupts any actively growing weeds present. The primary methods of control using this technique include: 1.) exhaustion of plant reserves, 2.) promotion of withering, and 3.) depriving the plant of any capacity to regenerate (Chicouene, 2007). Observations indicate that the type of plant injury inflicted and the biology of the plant, specifically life cycle, influence level of weed control (Chicouene, 2007). According to recent studies, exhaustion of plant reserves appeared to be more suitable against plants with deep regenerating organs, whereas plant withering favored plant species with sprouting organs near the soil surface (Chicouene, 2007).

Use of Herbicides in Flue-Cured Tobacco

Herbicides are often considered the primary method of weed control in flue-cured tobacco. This is in part due to herbicide options available, level of efficacy, broad spectrum control, and cost effectiveness compared to other inputs. However, total reliance on herbicides is not economically feasible, less effective, environmentally detrimental, and unsound weed management (Collins and Hawks, 2013; Vann et. al., 2016). Most importantly, overuse of herbicides has led to the rapid evolution of herbicide resistant weeds (Beckie, 2006; Egan et. al., 2011; Powles and Yu 2010). Despite increasing levels of resistance to various modes of action, herbicides will continue to be a critical component of future weed management strategies (Owen, 2016).

Chemical weed control options in tobacco are limited. The following herbicides, characterized by mode of action, are currently labeled for use in flue-cured tobacco: inhibition of protoporphyrinogen oxidase (sulfentrazone and carfentrazone, WSSA group 14), inhibition of carotenoid biosynthesis, (clomazone, WSSA group 13), inhibition of microtubule assembly (pendimethalin, WSSA group 3), inhibition of lipid synthesis (pebulate, WSSA group 8), inhibition of cell division (napropamide, WSSA group 15), and inhibition of acetyl CoA carboxylase (sethoxydim, WSSA group 1) (York, 2008; Lingenfelter and Hartwig, 2013). All materials listed will provide consistent control of certain weed species with minimal crop injury if label recommendations are followed.

The most widely used herbicides in flue-cured tobacco include pendimethalin, sulfentrazone, and clomazone (Fisher et. al., 2006). Pendimethalin is a member of the dinitroaniline chemical family. Materials within this classification are considered meristematic inhibitors that interfere with the plant’s cellular division or mitosis (Anonymous, 2016b). Like other dinitroanaline herbicides, pendimethalin is absorbed by both roots and shoots of emerging seedlings but are not readily translocated (Triantafyllidis et. al., 2009). Currently, pendimethalin can be applied pre-plant incorporated (PPI) or at layby as a directed spray in flue-cured tobacco for control of annual grasses and certain broadleaf weeds (Anonymous 2016b). The soil incorporation of pendimethalin is recommended due to stimulation of herbicide activity and reduction of sensitivity to light degradation (Vann et al., 2016; Rytwo et. al., 2005). However, stunting as a result of root injury has been observed in tobacco due to incorporation of pendimethalin. Potential reasons for this occurrence include environmental and/or soil conditions during time of application, unsatisfactory incorporation, high use rates, and tank-mixing two or more herbicides in a single application (Vann et al., 2016). Nevertheless, soil-applied herbicides such as pendimethalin remain a critical component in managing weed population shifts due to overreliance of herbicides such as glyphosate (Culpepper, 2006).

Sulfentrazone is labeled for control of susceptible broadleaf, grass, and sedge weeds in tobacco (Anonymous, 2016c). Activity on select weed species is obtained due to inhibition of protoporphyrinogen oxidase, an enzyme located in the chlorophyll biosynthesis pathway (Dayan et. al., 1997). Unlike other herbicides with a similar mode of action, sulfentrazone has excellent preemergence (PRE) activity, thereby making it suitable for a tobacco cropping system (Dayan et al., 1997). In addition, sulfentrazone is the only herbicide labeled for use in tobacco that is efficacious on morningglory (*Ipomoea* spp.) and purple nutsedge (*Cyperus rotundus* L.)(Fisher and Smith, 2003).

On occasion, early season stunting of tobacco has been observed following sulfentrazone application. Reasons for such occurrence are likely due to PPI instead of pre-transplant (PRE-T) applications, non-uniform incorporation, and environmental stresses (Vann et al., 2016). Studies have been conducted to determine flue-cured tobacco tolerance to sulfentrazone based upon uptake, translocation, and metabolism. Fisher et al. (2006) concluded that tolerance of tobacco to sulfentrazone is a result of metabolism. Data suggests that when sulfentrazone was used alone, 66 percent of the ^{14}C-sulfentrazone in the leaves was metabolized after only 3 hours

(Fisher et al., 2006). Therefore, under favorable conditions that promote rapid growth, injury from sulfentrazone is likely to be minimal.

Clomazone is labeled for control of susceptible grass and broadleaf weed species in tobacco (Anonymous, 2016a). Activity on select weed species is obtained due to inhibition of carotenoid biosynthesis. Specifically, this compound reduces or stops the accumulation of plastid pigments in susceptible species by inhibiting an enzyme of the terpenoid pathway resulting in a white, yellow, or pale green plant (Norman et. al., 1990). However, the exact enzymatic site of clomazone activity is still undetermined (Norman et al.,1990). According to label specifications, clomazone may be applied PRE-T or within seven days POST-transplanting (Anonymous, 2016a). Multiple timings of application offer growers flexibility while maintaining similar levels of weed control (Weeds, 2016). Due to herbicidal characterisics of clomazone, leaf whitening has been observed on tobacco. However, Scott et al. (1994) determined tobacco transplants to be extremely tolerant of clomazone. Such event is often not of concern since foliar symptoms are transient and root growth is not restricted (Vann et al., 2016).

Clomazone tank mixed with sulfentrazone PRE-T has proven to be a very effective weed management strategy. This in part due to the increased spectrum of weed control achieved when both herbicides are used simultaneously (Vann et. al., 2016). In addition to weed efficacy, both greenhouse and field studies demonstrated a reduction in plant injury when a mixture of sulfentrazone and clomazone was used compared to sulfentrazone alone (Fisher et. al., 2000). This statement can be supported based upon differences in rate of herbicide metabolism within a tobacco plant. Fisher et al. (2006) observed that the addition of clomazone significantly and consistently increased metabolism of the ^{14}C sulfentrazone in the leaves at three, six, and nine hours after treatment (HAT) compared to ^{14} C sulfentrazone alone. Despite findings, environmental factors can influence rate of uptake, translocation, and metabolism (Fisher et. al., 2006); therefore, applicators should still utilize materials based upon label recommendations.

Justification of Work

The implementation of a comprehensive weed management program in tobacco is a necessity in order to produce optimum leaf yield and quality. This approach must incorporate the use of herbicides, crop rotation, cultivation, hand removal, and early stalk and root destruction. With respect to herbicide selection, only seven active ingredients are currently labeled for use in flue-cured tobacco. Further, only two (napropamide and pendimethalin) are labeled at layby (last cultivation pass) and one (carfentrazone) after first harvest (Fisher et. al., 2016). This indicates the need for additional herbicide options, specifically POST-layby, in order to maintain season long weed control.

Weed species such as Palmer amaranth are deemed problematic due to various characteristics such as rate of growth, competition, seed production, and resistance to herbicides. Palmer amaranth seed may germinate from soil as early as March 1 until as late as October 1 and will typically flower between September and October (Keeley et. al., 1987). As a result, weed species that escape management practices maintain the ability to reproduce, allowing for replenishment of the soil seed bank (Bagvanthiannan and Norsworthy, 2012). Palmer amaranth seed production from plants emerging in the spring generally averages 200,000 to 600,000 seed plant^{-1} (Keeley et. al.,1987; Sosnoskie et. al., 2014). In addition, Palmer amaranth severed near the soil line the second week of July has been reported to grow back and produce 28,000 seed plant^{-1} (Sosnoskie et. al., 2014). These findings confirm Palmer amaranth’s ability to maintain production of seed at significant levels despite differences in time of germination.

Estimated flowering and seed production of Palmer amaranth is directly correlated with the time at which North Carolina producers harvest tobacco. Due to this observation, it is believed that viable weed seed is entering the U.S. flue-cured tobacco supply via the use of mechanical harvesters late in the growing season. As a result, export markets of U.S. leaf, such as China, have expressed concern regarding the presence of non-desirable weed seed in shipments. Furthermore, China reserves the right to reject shipment of U.S. leaf due to the introduction weed species listed on their quarantine list. These findings indicate the need for tobacco producers to utilize all weed management strategies at their disposal to maintain integrity of U.S. leaf and the tobacco industry as a whole.

Lastly, grower surveys were conducted in Wayne County, North Carolina during 2014 to determine which weed specie(s) was most difficult to control in flue-cured tobacco and what time of year weed pressure was greatest during the production season. Results were derived from twenty four individual tobacco farming operations distributed throughout Wayne County, North Carolina. Twenty out of twenty four participants (~83%) indicated that Palmer amaranth was the most common and difficult weed to control in flue-cured tobacco. In regards to intensity of weed pressure, eighteen out of twenty four participants (75%) expressed that they experienced the greatest weed pressure “at topping” and “after first harvest.”

Results from this survey support the need for evaluation of non-tobacco labeled for late season application. Post emergence herbicides applied after harvest for weed control has proven to be an important aspect of sustainable management to prevent seed production and subsequent spread of herbicide-resistant species (Crow et. al., 2015). Minimizing seed bank replenishment of problematic weeds is essential to the ultimate success of managing all herbicide resistant weed species.

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Chapter Two

The Effect of Herbicide Application and Timing on Weed Control, Crop Injury, Leaf Yield, and Quality of Flue-Cured Tobacco (*Nicotiana tabacum* L.)

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ABSTRACT

Research was conducted in two environments in 2014, 2015, and 2016 to determine the effects of the following herbicides for use in tobacco: *S*-metolachlor, sulfentrazone, trifloxysulfuron, fomesafen, glufosinate, mesotrione, linuron, and carfentrazone. Herbicides were applied before topping (BT) and after first harvest (AH) in order to quantify their effect on crop injury, weed control, leaf yield, quality, value, and chemistry of flue-cured tobacco. An application of sulfentrazone and clomazone[3] was applied pre-transplant (PRE-T) across all treatments while one treatment containing only sulfentrazone and clomazone PRE-T served as the control. Visual ratings of crop injury and control of Palmer amaranth were taken one to two weeks after treatment (WAT). Leaf yield was determined by stalk position and assigned an official USDA grade. Crop value was calculated based upon leaf yield and quality.

Limited Palmer amaranth was present at the LCPRS site, thus no significant difference in control was observed among treatments over three years. With respect to crop injury, differences were found from BT applications of glufosinate and mesotrione in 2015. Significant injury was detected in 2016 when compared to the control from the applications of sulfentrazone BT,

fomesafen BT, glufosinate BT, mesotrione BT, linuron BT, and carfentrazone BT. Despite crop injury from the above herbicides, yield, quality, value, and leaf chemistry were not affected in 2014 and 2016.

Differences were observed in 2015 for cured leaf yield, value, and reducing sugars. It is difficult to conclude that herbicide applications influenced leaf yield given limited crop injury and the absence of Palmer amaranth. However, the presence of soil-borne diseases, primarily Black Shank (Phytophthora nicotianae) was confirmed late season in isolated locations within the experiment. As a result, it is likely that root and stalk infection affected yield potential and value within certain plots.

Greater Palmer amaranth pressure was present at the UCPRS site. As a result, differences in control were observed during 2015 but not in 2014 and 2016. Specifically, the application of sulfentrazone BT, linuron BT, glufosinate BT, and fomesafen BT resulted in 100, 100, 99, and 97% Palmer amaranth control respectively, resulting in a significant difference when compared to the control (88%). Only trifloxysulfuron BT and linuron BT demonstrated greater Palmer amaranth control (90 and 100%, respectively) compared to trifloxysulfuron AH and linuron AH (75 and 89%, respectively).

Crop injury was observed from mesotrione BT and AH, glufosinate BT, and carfentrazone BT all three years while crop injury from glufosinate AH, carfentrazone AH, linuron BT and AH occurred in 2015 and 2016. Crop injury from sulfentrazone BT, fomesafen BT and AH occurred only in 2016. Leaf yield, quality, value, and chemistry were not affected by any of the herbicide applications.

NOMENCLATURE

Nicotiana tabacum L., tobacco.

KEY WORDS

herbicide, crop injury, weed control.

INTRODUCTION

Tobacco (*Nicotiana tabacum* L.) is considered a crop of significant economic importance to certain countries worldwide. In 2015, approximately four billion kilograms of leaf was produced collectively across all tobacco growing regions, resulting in a global cigarette market value of US$698.5 billion (Brown, 2015; MacGuill, 2016). Within the United States, 69,201 ha of tobacco was harvested in North Carolina, resulting in 169 million kilograms of cured leaf produced (Crop Production Summary, 2015). Assuming an average price of US$4.11/kg of cured leaf, total value of tobacco produced in North Carolina is estimated to be US$695 million (Crop Values Summary, 2015).

Importance of Herbicides in Weed Management

Herbicide resistant weeds have complicated weed management programs in multiple agronomic crops. Specifically, the presence of glyphosate resistant (GR) weeds has required growers to alter management strategies for weed suppression and to reduce seed bank populations of problematic weeds. Growers must employ multiple weed management strategies, such as crop rotation, tillage, and hand weeding, along with herbicides to effectively control weeds and reduce potential for resistance development.

The use of herbicides has been widely adopted in developed countries due to cost effectiveness and efficacy on target weeds (Owen, 2016). Soil-applied and POST-applied herbicides are often required for effective weed management in crop production systems (Buchanan 1992; Wilcut and Askew 1999). Everman et al. (2009) concluded that the lack of a soil applied PRE herbicide resulted in significant cotton lint yield losses in 22 out of 27 observations. These findings support the importance of a PRE herbicide treatment to avoid early season competition from weed species (Everman et. al., 2009).

It can be argued that the use of a timely POST herbicide is critical to providing season long weed control. Barnett et al. (2013) evaluated the effectiveness of glufosinate applied POST to Palmer amaranth compared to no POST application in the presence of pendimethalin applied PRE. Palmer amaranth was 13 cm in height during time of application. Results indicated that 90% control was achieved from the glufosinate POST treatment compared to 29% control in the absence of a POST application. Findings support that problematic weeds such as Palmer amaranth require timely POST herbicides in addition to PRE herbicides due their physiological characteristics and competiveness with multiple crops.

Due to the introduction herbicide resistant weed species, a proactive approach to weed management must be considered. It is known that the selection for weeds resistant to glyphosate resulted in the reoccurring usage of the material with little to no diversity in weed management strategies (Beckie, 2011). Diversification within weed management involves the use of herbicides with different modes of action (MOA) within growing seasons, herbicide MOA rotation among growing season in non-monoculture crop sequences and integration of non-herbicidal weed management tools (Beckie, 2011). Such strategies can delay herbicide resistance due to the altering of target sites at which weeds are controlled (Beckie, 2011).

Tobacco Tolerance to Select Herbicide Modes of Action

Herbicides are still considered a critical management tool for weed control in the production of flue-cured tobacco. Despite limited selection, the herbicides have historically provided growers with acceptable weed control and minimal crop injury, if used according to label recommendations.

The number of new herbicides registered for a particular crop has decreased over the past several years (Duke, 2012). As a result, growers have been challenged to manage herbicide resistant weeds in the absence of any new herbicides. Leon and Tillman (2015) emphasized the importance of identifying herbicide tolerant breeding lines; both registered and not registered for a particular crop. Early identification would allow plant breeders to take specific steps to increase the level of tolerance to key herbicides for future cultivars (Leon and Tillman, 2015). Furthermore, identification of crop tolerance herbicides currently not registered for a specific crop could increase the number of herbicides available for use. Most importantly, this may allow growers to utilize additional MOA's not previously available.

Tolerance to Acetolactate Synthase Inhibitiors (ALS). Table 1 outlines tolerance of tobacco to select MOA's currently registered for use. However, research suggests that tobacco has expressed some level of tolerance to additional MOA's outside of current registrations. Experiments were conducted in Kentucky during 2004 and 2005 to evaluate the level of crop injury and weed control of two experimental herbicides, trifloxysulfuron and halosulfuron, on no-till dark tobacco. Experimental herbicide treatments made after transplanting included trifloxysulfuron at 5.3 g ai/ha or halosulfuron at 53 g ai/ha applied early postemergence over-the-top (EPOT) or late post-directed (LPD). Injury ratings taken 10 days after treatment of trifloxysulfuron and halosulfuron over two years resulted in crop injury of 11 to 19 percent and 18 to 34 percent respectively from EPOT applications (Bailey and Pearce, 2014). At three to four weeks after application, crop injury ranged from 8 to 14 percent for trifloxysulfuron and 12 to 19 percent for halosulfuron (Bailey and Pearce, 2014). With respect to LPD applications, crop injury was minimal (less than 5 percent) three to four weeks after application for both herbicides over two years (Bailey and Pearce, 2014). Results suggested that an EPOT application of these herbicides may not be accepted by growers or industry due to injury potential and residue concerns. However, a LPD application of either herbicide may be desired due to minimal crop injury observed and lack of current herbicides available post-transplant.

Additional research was performed at the Oxford Tobacco Research Station near Oxford, North Carolina in 1997 and 1998 to evaluate tobacco tolerance to diclosulam when applied pre-transplant (PRE-T) and postemergence over-the-top (POT) using three different application rates of 9, 18, and 27 g ai/ha (Bailey et al., 2001). PRE-T applications were made immediately before transplanting and POT applications were made four to five weeks after transplanting. Visual ratings of crop injury were taken three, five, seven, and eleven weeks after treatment (WATR) using a percentage scale from zero to 100, where zero represented no visual injury and 100 represented complete plant death (Bailey et. al., 2001). At three WATR, injury percentages across all treatments were less than two percent. At five WATR, diclosulam applied POT at 9, 18, and 27 g ai/ha resulted in 55, 75, and 80 percent crop injury respectively while PRE-T applications remained at two percent. At seven WATR, diclosulam applied POT at 9, 18, and 27 g ai/ha resulted in 40, 50, and 63 percent crop injury respectively while PRE-T applications ranged from 1 to 3 percent. At eleven WATR, diclosulam applied POT at 9, 18, and 27 g ai/ha resulted in 21, 38, and 49 percent crop injury respectively while PRE-T applications ranged from 2 to 3 percent (Bailey et. al., 2001). Results suggest diclosulam applied POT was unacceptable given the level of injury observed across all rates and time intervals. However, a LPD application of diclosulam may provide satisfactory results given tobacco's tolerance to diclosulam PRE-T. Additional research would be needed to support or reject this theory.

Imazaquin has also been evaluated to determine broadleaf weed control and crop tolerance of flue-cured tobacco. Herbicide treatments at a rate of 0.28 and 0.42 kg ai/ha were applied using the following application methods and timings: pre-plant incorporated (PPI), post bed-incorporated (PEI), over-the-top (PE-overtop), and early postemergence (E-post) (Walls et. al., 1987). PPI treatments were disked immediately after herbicide application while PEI treatments were incorporated on top of row beds formed prior to application. PE-overtop treatments were applied broadcast immediately after transplant while E-post treatments were applied three to four weeks after transplanting (Walls et. al., 1987). Results indicated that 55 percent crop injury was observed from the PPI treatments, regardless of application rate (Walls et. al., 1987). All other treatments resulted in crop injury of less than seven percent (Walls et. al., 1987). Application method at which experimental herbicides are applied as well as herbicide placement (root absorption vs. foliar absorption) can greatly influence the level of crop tolerance.

Tolerance to Protoporphyrinogen Oxidase Inhibitors (PPO). Research was conducted on the Bowen Research Farm near Tifton, Georgia from 1988 to 1990 to determine tobacco tolerance to fomesafen and its influence on weed control when used in tobacco. Treatments utilized were fomesafen at 0.4 and 0.6 kg ai/ha applied pre-transplant incorporated (PTI), pre-transplant (PRE-T), post-transplant (POS-T), postemergence-over-top (POT), and post-directed (PD) (Bridges and Stephenson,1991). PTI treatments were incorporated into previously formed beds; PRE-T treatments were applied to the bed prior to transplanting; POS-T treatments were applied over the top of tobacco immediately after transplanting; POT treatments were applied approximately 14 days after transplanting (DATR), and PD treatments were directed to the base of the plant and top of the bed approximately 35 DATR (Bridges and Stephenson, 1991).

In the 1988 experiment, ratings were taken (14 DATR) comparing the PTI, PRE-T, and POS-T treatments. Crop injury resulted in a percentage of 29, 30, and 36 respectively when the 0.4 kg ai/ha rate was applied and 44, 36, and 47 when the 0.6 kg ai/ha rate was applied (Bridges and Stephenson, 1991). A second rating was taken on June 6th comparing all treatments. The PD treatments resulted in 38 percent crop injury for both rates. Elevated levels are likely due to herbicide contact with lower leaves. For all other treatments, crop injury was six percent or less when the 0.4 kg ai/ha rate was used. At the 0.6 kg ai/ha rate, PTI, PRE-T, POS-T, and POT injury ratings were 10, 6, 15, and 5 respectively (Bridges and Stephenson, 1991).

The experiment was replicated again in 1989 to determine previously stated objectives. Ratings were taken on May 2nd (30 DATR) comparing PTI, PRE-T, POS-T, and POT treatments. Crop injury resulted in a percentage of 20, 7, 3, and 12 respectively when 0.4 kg ai/ha was applied and 42, 15, 28, and 18 when the 0.6 kg ai/ha was applied (Bridges and Stephenson, 1991). At 92 DATR, minimal injury (3 percent or less) was recorded only in the 0.6

kg ai/ha POS-T treatment and both PD treatments (Bridges and Stephenson, 1991). No significant differences were detected when compared across all treatments. Results indicated that tobacco was tolerant to fomesafen at both rates when used PRE-T, POS-T, and POT. Injury was more consistent when applied PPI at both rates when compared to other application methods (Bridges and Stephenson, 1991). Symptoms appeared to be transient and tobacco recovered from injury with no effect on leaf yield and quality (Bridges and Stephenson, 1991).

Tolerance to Cell Division Inhibitors. Research was conducted in Croatia from 2002 to 2003 to determine the efficacy of different herbicide combinations, rates, and application methods on weed control in tobacco. Herbicides combinations of interest were *S*-metolachlor and clomazone (1,152 and 288 g ai/ha) applied broadcast before transplanting; *S*-metolachlor (1,152 g ai/ha) applied broadcast preemergence followed by clomazone (144 g ai/ha) applied postemergence in bands 40 cm wide; and acetochlor (1,500 g ai/ha) applied broadcast pre-transplant (Budimir et. al., 2003). Despite inconsistencies in herbicide efficacy due to the absence of rainfall at select locations, visible phytotoxicity was not observed in any treatment combination (Budimir et. al., 2003).

Efficacy of Selected Herbicides on Palmer Amaranth (*Amaranthus palmeri*) in other Crops

S-metolachlor. *S*-metolachlor, a member of the chloroacetamide chemical family, inhibits cell division and synthesis of very long-chain fatty acids (York, 2008). It is widely used in multiple cropping systems due to its residual activity, crop safety, and compatibility with other tank mix partners. Studies have shown that Palmer amaranth control systems containing *S*-metolachlor within one day after planting (DAP) have resulted in greater than or equal to 99 percent control through 74 (DAP) of sweet potato (Meyers et. al., 2013). An additional study in cotton concluded that pendimethalin PRE, followed by *S*-metolachlor and glufosinate POST resulted in greater than 95 percent control of Palmer amaranth (Everman et. al., 2009).

Trifloxysulfuron. Trifloxysulfuron, a member of the sulfonylurea chemical family, inhibits the acetolactate synthase (ALS) enzyme (York, 2008). It is labeled for use in cotton, sugarcane, and transplanted tomato (Anonymous, 2016b). It has been adopted due to its low toxicological properties, favorable environmental profile, low use rate, efficacy on multiple weeds species, and residual activity (Grichar and Minton, 2007). Studies have indicated that the following herbicide systems have provided 100 percent control of Palmer amaranth: *S*-metolachlor applied PRE followed by trifloxysulfuron late postemergence (LPOTT); glyphosate applied early postemergence (EPOTT) and mid-postemergence (MPOTT) followed by trifloxysulfuron alone or in combination with prometryn (LPOTT) (Grichar and Minton, 2007). Despite excellent control achieved from the use of trifloxysulfuron, growers must consider the presence of ALS resistant Palmer amaranth and employ additional weed management strategies to prevent resistance development.

Fomesafen. Fomesafen, a member of the diphenyl ether chemical family, inhibits the protoporphyrinogen oxidase enzyme in the porphyrin biosynthesis pathway in plants and animals (Caquet et al., 2005). It is currently registered for use in cotton, dry beans, snap beans, potatoes, and soybeans (Anonymous, 2016e). Since the introduction of glyphosate-resistant (GR) Palmer amaranth, fomesafen has become a popular herbicide choice POST due to its efficacy on GR Palmer amaranth and residual activity. Research conducted in soybeans concluded that a grass and broadleaf herbicide applied PRE followed by fomesafen POST increased Palmer amaranth control in six of seven environments at 30 days after POST herbicide application (DAPH) and in all environments 90 DAPH (Whitaker et. al., 2010). Results indicated that an average of 93 percent control was achieved across seven environments when fomesafen was applied POST compared to 55 percent with no POST herbicide. At 90 DAPH, 81 percent control was present when fomesafen was applied POST compared to 40 percent with no POST herbicide. Results further indicate that GR weed species, specifically Palmer amaranth, can be managed through the use of soil-applied, residual herbicides PRE followed by additional residual herbicides POST. However, it is possible that the application of two herbicides with the same mode of action (PPO) would increase selection pressure for additional herbicide resistance (Whitaker et. al., 2010). Such findings would be detrimental to weed management due to the rapid loss of herbicide efficacy to resistant weed species.

Glufosinate. Glufosinate, a member of the phosphinic acid chemical family, inhibits the glutamine synthetase enzyme (EC 6.3.12) and thereby causes rapid accumulation of ammonia and glyoxylate within the plant, eventually leading to cell membrane disruption and necrosis (Devine et. al., 1993; Hinchee et. al., 1993). It is currently registered for use in canola, corn, cotton, and soybeans that contains the LibertyLink® technology. In addition, the material may be used in non LibertyLink® cotton through the use of a hooded sprayer or as a broadcast, burn-down application before planting or prior to crop emergence of any conventional or transgenic variety of canola, corn, cotton, soybean, or sugar beet (Anonymous, 2016c). Due to confirmation of resistance weed species to other commonly used herbicides, adoption of the LibertyLink® technology has increased due to its ability to control problematic weeds POST in combination with residual herbicides. Studies in soybeans have shown that herbicide programs containing standard PRE herbicides followed by two POST applications of glufosinate alone resulted in greater than 95 percent control of Palmer amaranth (Ahmed and Holshouser, 2014). However, two applications of glufosinate applied one week and five weeks after soybean planting (WAP) in the absence of PRE herbicides have yielded control not significantly different at two, six, eight WAP when compared to treatments containing a PRE herbicide (Ahmed and Holshouser, 2014). A significant difference was indicated at four WAP when PRE herbicides were used in combination with glufosinate compared to glufosinate alone (Ahmed and Holshouser, 2014). A decrease in control between applications of glufosinate applied alone is likely due to the absence of residual activity. Despite effective control achieved from two applications of glufosinate alone, this practice is not recommended due to the increased selection pressure placed on potential glufosinate-resistant biotypes (Ahmed and Holshouser, 2014). Further, un-timely applications and weed escapes are likely due to the robust growth habit of Palmer amaranth, resulting in unsatisfactory control. To reduce the amount of applications of glufosinate in a crop year, the use of PRE herbicides followed by residual herbicides tank-mixed with glufosinate is recommended.

Mesotrione. Mesotrione, a member of the triketones chemical family, inhibits 4-hydroxyphenyl-pyruvate-dioxygenase (4-HPPD) (York, 2008). This enzyme is involved in the biosynthesis of quinone, which is a key factor in the synthesis of carotenoids (York, 2008). Due to the disruption of carotenoid pigments, foliar tissue is "bleached" and plant death occurs. Mesotrione is labeled for use in field corn, seed corn, yellow popcorn, sweet corn, and select specialty crops (Anonymous 2017a). HPPD inhibiting herbicides such as mesotrione has been commonly used for in weed control in corn due to their ability to control GR weeds (Wiggins et. al., 2015). Furthermore, HPPD's offer broad spectrum weed control, flexible application timings, tank-mix compatibilities, and crop safety (Bollman et. al., 2008; Stephenson and Bond, 2012; Walsh et. al., 2012). In most cases, mesotrione is tank-mixed with atrazine and/or glyphosate to broaden spectrum of weed control to include grass species. Studies have shown that the herbicide mixture containing glyphosate, *S*-metolachlor, mesotrione, and atrazine provided 96 percent control of Palmer amaranth seven days after treatment (DAT) compared to 77 percent when just glyphosate and atrazine was applied (Wiggins et. al., 2015). Palmer amaranth was 15 cm in height at the time of application (Wiggins et. al., 2015). Since *S*-metolachlor has no activity on existing weeds, it is evident that the addition of mesotrione enhanced weed control of Palmer amaranth.

Linuron. Linuron, a member of the urea chemical family, inhibits the electron flow in photosystem II of the light reaction of photosynthesis, resulting in the production of free radicals and rapid plant death (York, 2008). Linuron is labeled for use in corn, cotton, potato, sorghum, soybeans, winter wheat, and select specialty crops (Anonymous, 2016d). Despite being labeled PRE in select crops, linuron is generally applied postemergence-directed (POST-DIR) to the row middle and/or the base of the crop. Riar et. al. (2012) reported that for consistent control within cotton row middles the final herbicide application should contain a residual herbicide effective on Palmer amaranth such as linuron. Johnson (1971) also concluded that Vernolate (*S*-propyl dipropylthiocarbamate) applied pre-plant incorporated or injected in bands 7.6 cm apart followed by linuron POST-DIR controlled broadleaf weeds 89-100 percent across three crop years (1968-1970) in soybeans.

Purpose of Research

Current selection of herbicides registered for use in flue-cured tobacco is extremely limited. As a result, the potential for further contamination of US leaf via weed seed(s) exists. Given the known tolerance of tobacco to various herbicide MOA's as well as efficacy of materials on problematic weeds, additional herbicides were evaluated. The objective of this study was to determine the effect of applications of herbicides not currently registered for use in tobacco on plant injury, weed control, leaf yield, quality, value, and chemistry of flue-cured tobacco.

MATERIALS AND METHODS

Field Procedures

Research was conducted during 2014, 2015, and 2016 to determine the effects of various non-tobacco labeled herbicides applied late season to flue-cured tobacco. The primary objectives of this study were to document percent injury to tobacco, percent control to certain weed species, specifically Palmer amaranth, and its effect on leaf yield, quality, value, and chemistry. Field research was conducted at the Lower Coastal Plain Research Station (LCPRS) in Kinston, North Carolina and the Upper Coastal Plain Research Station (UCPRS) near Rocky Mount, North Carolina. Transplant date, pH, humic matter (Table 2), and cumulative rainfall (Table 3) varied by location and year while soil series remained the same (Table 2). Standard management practices of tobacco were performed by personnel at each research station. The cultivar used throughout the duration of the study was NC 196[1]. The only variable applied to the study was the application of a select herbicide before topping (BT) or after first harvest (AH). Application timings were selected to simulate maximum injury potential due to the plant being fully exposed (BT) compared to a directed application under plant leaves (AH). BT and AH applications were delivered approximately 70 and 90 days after transplanting (DAT), respectively. Topping of the tobacco plant refers to the removal of the terminal bud that produces a flower (Collins and Hawk, 2013). Topping occurs once tobacco becomes fully grown and accumulates between 20 and 22 leaves, which typically occurs 8 to 10 weeks after transplanting. Physical removal of reproductive structures allows the plants energy to be utilized for leaf production instead of seed production.

At all locations, all treatments were replicated four times in a randomized complete block design. Each plot consisted of one row with a common border row between treatments. At the LCPRS in 2014 and 2015, the plot dimensions were 1.13 meters wide by 12.19 meters long. In 2016, plot dimensions were 1.13 meters wide by 15.24 meters long. At the UCPRS in 2014 and 2015, the dimensions were 1.22 meters wide by 12.19 meters long. In 2016, the dimensions were 1.22 meters wide by 15.24 meters long. One row was harvested four times by stalk position to quantify leaf yield and quality. A single weighted composite sample representing all four stalk positions was collected from each plot for measurement of total alkaloids and reducing sugars.

Early Season Weed Management Practices

Tillage implements were used for standard field bed preparation prior to transplanting at each location to ensure the absence of weeds. Row shapers were used in the formation of a high row ridge to promote adequate drainage and a larger root system (Collins and Hawks, 2013). Post-transplant cultivation events were performed to promote the continued buildup of a high row ridge and to eliminate the presence of early season weed species. The number of cultivations each season was determined by personnel from each location based upon soil and environmental conditions. On average, post-transplant cultivation was suspended approximately 45 days after transplant. Hand weeding was not performed to ensure weed pressure was present at time of application.

Experimental Treatment

A pre-transplant (PRE-T) application of sulfentrazone[2] and clomazone[3] was applied broadcast across all treatments at a rate of 175 g/ha^{-1} and 830 g/ha^{-1}, respectively. These materials were selected to provide broad spectrum control to early season weed species. No additional herbicides were applied directly after transplanting or at lay-by.

The experiment contained 17 total treatments evaluating eight different herbicides. The nine herbicides applied include *S*-metachlor[4], sulfentrazone, trifloxysulfuron[5], fomesafen[6], glufosinate[7], mesotrione[8], linuron[9], and carfentrazone[10]. Each herbicide was applied at before topping or after first harvest at both locations (Table 4). The treatment containing only sulfentrazone and clomazone applied PRE-T served as the control. Crop height at time of application was approximately 165 cm.

The rates applied were based upon current label recommendations established in other cropping systems and are found in Table 5. A non-ionic surfactant was used with trifloxysulfuron, fomesafen, glufosinate, mesotrione, linuron, and carfentrazone to improve efficacy as recommended by the manufacturer.

A CO_2 pressurized backpack sprayer containing a 50.8 cm boom and two TP11003-VS nozzles[11] were used to apply all treatments. In addition, a total spray volume of 187 L/ha was used across all treatments. The target site consisted of the entire row middle and a significant portion of the plant bed. Applications were delivered to both sides of the harvest row. In order to simulate a worst case scenario for potential crop injury, no shields or hoods were placed around the nozzle during application.

Data Collection

Visual ratings of crop injury and control of Palmer amaranth were performed in all six environments. Each rating was based upon a scale from zero to 100. A rating of zero would represent no injury symptoms present and 100 would represent the presence of total plant death. Visual injury percentages were based upon severity of leaf chlorosis and/or necrosis, number of plants exhibiting chlorosis and/or necrosis, and movement of symptoms throughout the plant relative to the control for each replication. Visual control percentages of Palmer amaranth were based upon the number of weeds and their respective size throughout the treated area relative to the control treatment. Each year, data were collected between one and two weeks after treatment (WAT) to document percent injury of tobacco and percent Palmer amaranth control. After curing, leaves were weighed to determine yield and assigned a USDA government grade. The grade index is a number between one and 100 that assigns value to the quality of a particular lot of flue-cured tobacco as measured by the USDA (Bowman et. al., 1988). In addition, total alkaloids and percent reducing sugars were determined by the North Carolina State University Tobacco Analytical Services Lab. Data were subjected to an analysis of variance (ANOVA) using the PROC GLM procedure in SAS Version 9.4[12]. Treatment means were separated using Fisher's Protected LSD at $p \leq 0.05$.

RESULTS

A significant difference was noted when crop injury and Palmer amaranth control were pooled across locations due to environmental conditions, particularly rainfall. Therefore, the results of those parameters are reported by environment. However, leaf yield, quality, and value are pooled across five environments, with Kinston 2015 being reported alone.

Crop Injury as a Result of Herbicide Application Before Topping (BT)

2014. At the LCPRS, no visible crop injury was observed across all treatments (Table 6). At the UCPRS, the application of mesotrione, glufosinate, and carfentrazone resulted in measurable crop injury when compared to the control (Table 6). Injury from mesotrione was greater than all other treatments (13%) was followed by glufosinate and carfentrazone at 4% and 3%, respectively.

2015. At the LCPRS, minimal crop injury was observed from the application of glufosinate (5%) and mesotrione (4%), which was greater that the control (Table 7).

At the UCPRS, crop injury was observed from the application of mesotrione, glufosinate, and carfentrazone (16, 5, and 2%, respectively) (Table 7). Injury from mesotrione and glufosinate resulted in a significant difference when compared to the control while carfentrazone was not significantly different when compared to the control.

2016. Crop injury was observed at the LCPRS from the BT application of carfentrazone (23%), glufosinate (20%), fomesafen (18%), sulfentrazone (14%), and mesotrione (10%) (Table 8). Each injury evaluation was significantly different from the control (Table 8).

At the UCPRS, tobacco injury was observed with glufosinate (12%), carfentrazone (10%), linuron (6%), sulfentrazone (5%), fomesafen (5%), and mesotrione (1%) (Table 8). All treatments exhibiting injury, with the exception of mesotrione, were significantly different when compared to the control.

Crop Injury as a Result of Herbicide Application Before Topping (BT) and After First Harvest (AH).

2014. No visible injury was observed across any treatments at the LCPRS (Table 9). At the UCPRS, mesotrione applied BT was the only herbicide that resulted in crop injury (13%) (Table 9). However, injury was significantly different when compared to the control. Injury that was observed from other herbicides (glufosinate and carfentrazone) after BT application was removed due to harvest of lower leaves. As a result, no injury was recorded after 1st harvest ratings despite previous injury (Tables 6, 9).

2015. Only minor injury (4%) was observed from the mesotrione BT application at the LCPRS (Table 10). However, injury was significantly different when compared to the control. At the UCPRS, significant injury was observed from mesotrione BT and linuron BT, while minimal injury was noted from glufosinate AH and linuron AH. Specifically, mesotrione and linuron BT resulted in a significant difference when compared to the control while glufosinate and linuron AH exhibited no significant difference when compared to the control (Table 10).

2016. Injury was observed from the following herbicides at the LCPRS: linuron BT (53%), mesotrione BT (16%), linuron AH (5%), glufosinate AH (3%), carfentrazone AH (3%), fomesafen AH (1%), and sulfentrazone AH (1%) (Table 11). Injury from linuron BT and mesotrione BT was significantly greater when compared to the control. Injury from linuron AH, glufosinate AH, carfentrazone AH, fomesafen AH, and sulfentrazone AH was not significant when compared to the control (Table 11).

At the UCPRS, visible crop injury was recorded from the applications of linuron BT (13%), mesotrione BT (5%), linuron AH (3%), mesotrione AH (2%), glufosinate AH (1%), and fomesafen AH (1%) (Table 11). Data analysis indicated a significant difference when linuron BT was compared to the control, while injury from mesotrione BT, linuron AH, mesotrione AH, glufosinate AH, and fomesafen AH resulted in no significant difference when compared to the control.

Palmer amaranth Control as a Result of Herbicide Application Before Topping (BT)

2014. Minimal weed pressure was present at the LCPRS site. As a result, 100 percent Palmer amaranth control was achieved across all treatments (Table 6). At the UCPRS, weed pressure was greater compared to the LCPRS. Despite an increase in weed populations, no significant difference was detected from any herbicide applications when compared to the control (Table 6).

2015. Minimal weed pressure was present at the LCPRS site. As a result, 100 percent Palmer amaranth control was achieved across all treatments (Table 7). At the UCPRS, weed pressure was greater compared to the LCPRS. A significant difference in Palmer amaranth control was detected when *S*-metolachlor (80%) and trifloxysulfuron (93%) was compared to the control (100%) (Table 7). Differences in control are likely due to uneven distribution of weed pressure throughout replications. In addition, certain herbicides such as *S*-metolachlor are not effective on existing weeds, thereby limiting efficacy if weeds are already established. Lastly, it has been hypothesized that ALS resistant Palmer amaranth is present at this location. If so, ALS-inhibiting herbicides such as trifloxysulfuron may not produce desired results.

2016. Minimal weed pressure was present at both the LCPRS and UCPRS sites. All treatments at the LCPRS yielded 100 percent Palmer amaranth control (Table 8). At the UCPRS, all treatments resulted in 100 percent Palmer amaranth control with the exception of *S*-metolachlor (99%) (Table 8).

Palmer amaranth Control as a Result of Herbicide Application Before Topping (BT) and After First Harvest (AH)

2014. As previously mentioned, minimal weed pressure was present at the LCPRS. As a result, 100 percent Palmer amaranth control was achieved across all treatments despite different herbicide application timings (Table 9). At the UCPRS, no significant difference in Palmer amaranth control was achieved across all herbicide treatments when compared to the control despite two different application timings (Table 9).

2015. Minimal weed pressure was present at the LCPRS. As a result, 100 percent Palmer amaranth control was achieved across all treatments despite different herbicide application timings (Table 10). At the UCPRS, Palmer amaranth control varied significantly depending upon herbicide and timing. The application of sulfentrazone BT, linuron BT, glufosinate BT, and fomesafen BT resulted in 100, 100, 99, and 97% Palmer amaranth control respectively, resulting in a significant difference when compared to the control (88%) (Table 10). Trifloxysulfuron AH was the only treatment that resulted in significantly less Palmer amaranth control (75%) when compared to the control (88%). The treatments containing *S*-metolachlor BT, *S*-metolachlor AH, sulfentrazone AH, trifloxysulfuron BT, fomesafen AH, glufosinate AH, mesotrione BT, mesotrione AH, linuron AH, carfentrazone BT, and carfentrazone AH resulted no significant difference when compared to the control. Trifloxysulfuron BT and linuron BT demonstrated greater Palmer amaranth control (90 and 100% respectively) compared to trifloxysulfuron AH and linuron AH (75 and 89% respectively) (Table 10). These results indicate that herbicide selection and timing can significantly impact efficacy of Palmer amaranth.

2016. Minimal weed pressure was present at both the LCPRS and UCPRS site. As a result, no significant difference in Palmer amaranth control was achieved at both locations despite two different application timings (Table 11).

Physical Characteristics, Chemical Characteristics, and Crop Value

Leaf yield. Cured leaf yield was not affected by the application of select herbicides applied either before topping (BT) or after 1st harvest (AH) when compared to the control despite injury symptoms observed at all locations except LCPRS 2015 (Table 12). With respect to crop injury, contact herbicides affected only lug grade leaf, resulting in insignificant yield loss since lugs represent only 13 percent of total plant weight (Figure 1). Injury symptoms from systemic herbicides, primarily mesotrione and linuron, appeared on leaf and tip stalk positions. Despite limited loss in leaf yield, it is likely that contracting companies will not desire such leaf due to herbicide residue concerns.

Leaf yield (*LCPRS 2015 only*). A significant difference in cured leaf yield was observed with all treatments when compared to the control except the following: sulfentrazone BT, glufosinate BT and AH, mesotrione AH, and linuron BT (Table 13). However, minimal injury (4%) was observed only with mesotrione BT while all other treatments resulted in zero visible injury (Table 13). It is difficult to conclude that herbicide applications influenced leaf yield given limited crop injury and the absence of Palmer amaranth. However, the presence of soil-borne diseases, primarily Black Shank (*Phytophthora nicotianae*) was confirmed late season in isolated locations within the experiment. As a result, it is likely that root and stalk infection affected yield potential within certain plots.

Grade Index. Cured leaf quality was not affected by the application of select herbicides applied either BT or AH when compared to the control despite occurrence of injury symptoms (Tables 12, 13).

Crop Value. No significant difference was observed with value of tobacco when herbicide applications were applied either BT or AH when compared to the control at all locations except LCPRS 2015 (Table 12). This conclusion was expected given no differences in leaf quality.

Crop Value (*LCPRS 2015 only*). A significant difference in value of tobacco was found when compared to the control for all treatments except the following: sulfentrazone BT, fomesafen AH, glufosinate BT, mesotrione AH, and linuron BT (Table 13). As previously stated, the presence of Black Shank likely resulted in a reduction in leaf yield, thereby reducing crop value.

Total Alkaloids. Total alkaloid accumulation in cured leaf was not affected by crop injury or Palmer amaranth control at any location when compared to the control (Tables 12, 13).

Reducing Sugars. A significant difference in reducing sugar content was observed when *S*-metolachlor AH, mesotrione BT, linuron BT, and carfentrazone BT was compared to the control (Tables 12, 13). Crop injury imposed on tobacco due to herbicide application may have influenced a reduction in sugar content in cured leaf. However, leaf quality was not affected due to a decrease in sugar content.

DISCUSSION

Crop Injury as a Result of Herbicide Application Before Topping

Mesotrione and linuron. Injury from mesotrione and linuron was likely a result of the plants ability to absorb the material via soil and foliar absorption. Due to the rainfall received around time of application (Table 3), both materials were able to move easily through the soil profile and be absorbed by plant roots. In addition, topping (hand removal of plant flowers) occurred shortly after application, thereby stimulating additional root growth and further uptake of each material. Since mesotrione is systemic within the plant, injury in the form of leaf bleaching was concentrated in the upper most portion of the plant above leaf positions directly contacted by the spray solution. When compared to mesotrione, linuron did not appear to be as mobile since uppermost leaves remained normal. However, lower and middle stalk leaves expressed leaf bleaching symptoms of linuron along leaf margins due to apoplastic mobility.

Carfentrazone, Fomesafen, Glufosinate, and Sulfentrazone. Injury was observed from glufosinate, carfentrazone, fomesafen, and sulfentrazone. Injury from all materials mentioned occurred due to spray droplet contact with lower leaves during application, resulting in necrotic leaf burn. Despite presence of injury, level of severity appeared to be minimal and would be acceptable with the addition of hoods or shields.

Crop Injury as a Result of Herbicide Application Before Topping and After First Harvest

Mesotrione and linuron. Root absorption by tobacco, continuous plant topping, and sequential rainfall and/or irrigation events led to increased injury of BT treatments over time. Given the highest level of injury observed from mesotrione (25%) and linuron (53%), these materials are not recommended for product registration in tobacco.

Carfentrazone, Fomesafen, Glufosinate, and Sulfentrazone. Injury that was observed from these materials BT were removed due to harvest of lower leaves. As a result, no injury was recorded after AH ratings despite previous injury being present. Minimal injury was observed from these materials when applied AH, thus supporting product registration for use in tobacco.

CONCLUSION

With the exception of the 2015 LCPRS site, herbicide at both timings did not affect leaf yield, quality, value, or leaf chemistry. However, significant crop injury was observed from several herbicides, primarily those possessing root absorption properties where tobacco does not have a natural tolerance (mesotrione and linuron). Given injury severity and probable detection of residue, it is likely that growers, product manufacturers, and contracting companies would oppose the use of these materials in tobacco.

In addition, injury was observed from contact herbicides, primarily BT. This occurred due to the presence of lower leaves intercepting spray droplets as no hoods or shields were used during application. However, contact herbicides applied AH resulted in no significant injury in any of the three years when compared to the control because they were directed below the crop canopy. Despite documentation of injury from multiple contact herbicides, no injury rating was greater than that of carfentrazone, which is currently registered for use AH in tobacco. With the implementation of shields and hoods and the limitation of application only after first harvest, the following herbicides, based upon data collected from this experiment, could still be viable options: sulfentrazone, fomesafen, and glufosinate. Lastly, herbicides such as *S*-metolachlor and trifloxysulfuron could also be considered for registration since previous studies have shown tobacco to be tolerant to these materials when the application does not come in contact with plant foliage. However, producers must be aware of potential carryover concerns to rotational crops given time of application during the growing season (Table 14).

Palmer amaranth control was not significantly improved based upon the initial rating taken after only the BT applications were applied in any of the three trial years. It is likely that residual activity through the use of sulfentrazone and clomazone PRE-T continued to suppress a broad spectrum of weed species through topping. In addition, early season cultivation was performed to ensure weed growth was minimized and herbicides were fully activated. Lastly, leaves were not removed prior to the before topping application. As a result, limited sunlight was able to penetrate to the soil surface due to partial canopy closure, thus delaying the emergence of weed species.

Palmer amaranth control was not statistically improved from the BT or AH herbicide applications based on the final rating after all treatments were applied in any of the six environments with the exception of the UCPRS site in 2015. This was likely due to minimal weed pressure, the effectiveness of sulfentrazone and clomazone PRE-T, cultivation, and competiveness of tobacco with weeds.

Palmer amaranth density was greatest at the UCPRS in 2015 when compared to the remaining five environments. All treatments that provided significantly greater weed control when compared to the control were applied BT. During time of application, Palmer amaranth that was emerged was less than 10 cm in height. With adequate spray coverage and volume, this allowed sulfentrazone, fomesafen, glufosinate, and linuron herbicides to achieve 96% control or greater of Palmer amaranth. This observation indicated that time of application and herbicide selection can impact efficacy of Palmer amaranth. During AH applications, lower leaves of tobacco were removed. This allowed for greater exposure of emerged weeds to sunlight, thus an increase in weed size at time of application. In addition, it is likely that sulfentrazone applied PRE-T began to dissipate, allowing for the additional emergence of broadleaf weed species.

One of the primary objectives of this experiment was to determine crop injury of tobacco if exposed to alternative herbicides not currently registered for use in tobacco. Research has proven the efficacy of the herbicides utilized in this experiment on Palmer amaranth if current recommendations are followed, but its effect on injury of tobacco was unknown. This experiment supports the idea that several herbicides may be considered appropriate for late season use in tobacco if proper recommendations are followed such as the use of hoods or shields that prevent herbicide contact with tobacco leaves. Most importantly, this research offers tobacco growers with alternative chemical control options. If registered, growers will have additional options to manage late season weeds and minimize seed bank replenishment of herbicide resistant weed species, thus reducing the potential for contamination of cured tobacco with viable weed seed.

SOURCES OF MATERIALS

[1] NC 196, Goldleaf Seed Company, Hartsville, SC 29550.

[2] Spartan® 4F, FMC Corporation, Philadelphia, Pennsylvania 19103.

[3] Command® 3ME, FMC Corporation, Philadelphia, Pennsylvania 19103.

[4] Dual Magnum®, Syngenta Crop Protection, LLC, Greensboro, North Carolina 27419.

[5] Envoke®, Syngenta Crop Protection, LLC, Greensboro, North Carolina 27419.

[6] Reflex®, Syngenta Crop Protection, LLC, Greensboro, North Carolina 27419.

[7] Liberty®, 280 SL, Bayer CropScience LP, Research Triangle Park, North Carolina 27709.

[8] Callisto®, Syngenta Crop Protection, LLC, Greensboro, North Carolina 27419.

[9] Linex® 4L, E. I. du Pont de Nemours and Company, Wilmington, Delaware 19898.

[10] Aim®, FMC Corporation, Philadelphia, Pennsylvania 19103.

[11] Teejet® TP11003-VS nozzles, Spraying Systems Co., Wheaton, IL 60189.

[12] SAS Institute Inc., Cary, NC 27513.

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Table 1. Active ingredients, trade names, and the modes of action for approved tobacco herbicides

Active Ingredient	Trade Name	Mode of Action
carfentrazone-ethyl	Aim®	Inhibition of protoporphyrinogen oxidase (PPO)
clomazone	Command® 3ME	Inhibition of carotenoid biosynthesis
napropamide	Devrinol® 50 DF	Inhibition of cell division
pendimethalin	Prowl®3.3 EC/Prowl®H_2O	Inhibition of microtubule assembly
sethoxydim	Poast®	Inhibition of acetyl CoA carboxylase (ACCase)
S-propyl butylethylthiocarbamate	Tillam®	Inhibition of lipid synthesis
sulfentrazone	Spartan® 4F	Inhibition of protoporphyrinogen oxidase (PPO)

*Tillam label derived from Zeneca Ag Products
http://www.sweetbeet.com/growernet/Resources/Pesticides/Labels/tillam_6e.PDF

Table 2. Soil series, taxonomic class, pH, %humic matter, transplanting date, and variety for each environment

Location/Year	Soil Series*	Taxonomic Class**	pH***	Humic Matter (%)***	Transplanting Date	Variety
LCPRS-2014[1]	Norfolk	Fine-loamy, kaolinitic, thermic Typic Kandiudults	5.5	0.60	April 30, 2014	NC 196
UCPRS-2014[2]	Norfolk	Fine-loamy, kaolinitic, thermic Typic Kandiudults	5.8	0.56	April 21, 2014	NC 196
LCPRS-2015[3]	Norfolk	Fine-loamy, kaolinitic, thermic Typic Kandiudults	5.4	0.51	April 20, 2015	NC 196
UCRPS-2015[4]	Norfolk	Fine-loamy, kaolinitic, thermic Typic Kandiudults	6.2	0.25	May 4, 2015	NC 196
LCPRS-2016[5]	Norfolk	Fine-loamy, kaolinitic, thermic Typic Kandiudults	5.8	0.51	April 21, 2016	NC 196
UCPRS-2016[6]	Norfolk/Lumbee	Fine-loamy, kaolinitic, thermic Typic Kandiudults/ Fine-loamy over sandy or sandy-skeletal, siliceous, subactive, thermic Typic Endoaquults	6.4	0.46	April 25, 2016	NC 196

[1] LCPRS-2014 Kinston, North Carolina

[2] UCPRS-2014 Rocky Mount, North Carolina

[3] LCPRS-2015 Kinston, North Carolina

[4] UCPRS-2015 Rocky Mount, North Carolina

[5] LCPRS-2016 Kinston, North Carolina

[6] UCPRS-2016 Rocky Mount, North Carolina

*https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx

**https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/soils/home/?cid=nrcs142p2_053587

***Soil samples were analyzed at the North Carolina Department of Agriculture and Consumer Services Agronomic Division using the Mehlich-3 Extraction Method.

Table 3. Monthly, cumulative, and 30 year average rainfall in each growing environment

	LCPRS[1]				**UCPRS[2]**			
Month	**2014**	**2015**	**2016**	**Average (1971-2000)**	**2014**	**2015**	**2016**	**Average (1971-2000)**
April	11.9	10.5	7.2	8.1	14.7	13.3	7.5	8.1
May	8.3	14.6	14.2	9.8	6.7	6.0	9.3	9.7
June	29.4	13.9	11.0	11.4	13.1	8.4	11.1	10.0
July	28.7	16.4	16.1	13.4	16.9	5.4	49.0	12.4
August	15.2	9.8	10.4	13.6	23.5	8.2	8.5	11.2
September	16.6	9.0	30.7	14.3	11.8	16.7	24.6	13.5
October	3.8	14.8	27.2	8.4	6.6	13.7	25.9	7.7
Total	113.9	89.0	116.8	79.0	93.3	71.7	135.9	72.6

[1] Lower Coastal Plain Research Station-Kinston, North Carolina

[2] Upper Coastal Plain Research Station-Rocky Mount, North Carolina

Table 4. Herbicide application date in each growing environment

Application Time	LCPRS-2014[1]	UCPRS-2014[2]	LCPRS-2015[3]	UCPRS-2015[4]	LCPRS-2016[5]	UCPRS-2016[6]
Pre-Topping	July 2	July 9	July 9	July 9	June 23	July 14
After 1st Harvest	July 28	July 19	July 28	August 24	July 14	August 12

Table 5. Herbicide active ingredient, trade name, application rate, and mode of action

Active Ingredient	Trade Name	Application Rate	Mode of Action
carfentrazone-ethyl	Aim®	52 g ai/ha	Inhibition of protoporphyrinogen oxidase (PPO), WSSA Group 14
glufosinate-ammonium	Liberty® 280 SL	588 g ai/ha	Inhibition of glutamine synthetase, WSSA Group 10
linuron	Linex® 4L	1107 g ai/ha	Inhibition of photosynthesis of photosystem II, WSSA Group 7
mesotrione	Callisto®	105 g ai/ha	Inhibition of 4-hydroxyphenyl-pyruvate-dioxygenase (HPPD), WSSA Group 27
S- metolachlor	Dual Magnum®	1398 g ai/ha	Inhibition of cell division, WSSA Group 15
sodium salt of fomesafen	Reflex®	279 g ai/ha	Inhibiton of protoporphyrinogen oxidase (PPO), WSSA Group 14
sulfentrazone	Spartan® 4F	280 g ai/ha	Inhibition of protoporphyrinogen oxidase (PPO), WSSA Group 14
sulfentrazone+ clomazone	Spartan® 4F +Command®3ME	175 g ai + 830 g ai/ha	Inhibition of protoporphyrinogen oxidase (PPO) + Inhibition of carotenoid biosynthesis, WSSA Group 14+13
trifloxysulfuron-sodium	Envoke®	85 g ai/ha	Inhibition of acetolactate synthase (ALS), WSSA Group 2

Table 6. Crop injury and Palmer amaranth control following before topping application at the Lower Coastal Plain Research Station (LCPRS) and Upper Coastal Plain Research Station (UCPRS) in 2014.[a]

	LCPRS		UCPRS	
Herbicide	**Injury**	**Control**	**Injury**	**Control**
	--------------------%	--------------------------	---------------------%	----------------------
S-metolachlor	0 a	100 a	0 c	90 a
Sulfentrazone	0 a	100 a	0 c	100 a
Trifloxysulfuron	0 a	100 a	0 c	98 a
Fomesafen	0 a	100 a	0 c	100 a
Glufosinate	0 a	100 a	4 b	100 a
Mesotrione	0 a	100 a	13 a	99 a
Linuron	0 a	100 a	0 c	100 a
Carfentrazone	0 a	100 a	3 b	100 a
Sulfentrazone+Clomazone[b]	0 a	100 a	0 c	100 a

[a] means followed by the same letter are not significant at $p \leq 0.05$.
[b] sulfentrazone and clomazone applied PRE-T only.

Table 7. Crop injury and Palmer amaranth control following before topping application at the Lower Coastal Plain Research Station (LCPRS) and Upper Coastal Plain Research Station (UCPRS) in 2015.[a]

	LCPRS		UCPRS	
Herbicide	**Injury**	**Control**	**Injury**	**Control**
	--------------------%	---------------------------	--------------------%	---------------------
S-metolachlor	0 c	100 a	0 c	80 c
Sulfentrazone	0 c	100 a	0 c	100 a
Trifloxysulfuron	0 c	100 a	0 c	93 b
Fomesafen	0 c	100 a	0 c	98 ab
Glufosinate	5 a	100 a	5 b	99 a
Mesotrione	4 b	100 a	16 a	97 ab
Linuron	0 c	100 a	0 c	99 a
Carfentrazone	0 c	100 a	2 bc	95 ab
Sulfentrazone+Clomazone[b]	0 c	100 a	0 c	100 a

[a] means followed by the same letter are not significant at $p \leq 0.05$.

[b] sulfentrazone and clomazone applied PRE-T only.

Table 8. Crop injury and Palmer amaranth control following before topping application at the Lower Coastal Plain Research Station (LCPRS) and Upper Coastal Plain Research Station (UCPRS) in 2016.[a]

	LCPRS		**UCPRS**	
Herbicide	**Injury**	**Control**	**Injury**	**Control**
	--------------------%--------------------------		----------------------%----------------------	
S-metolachlor	0 d	100 a	0 c	99 a
Sulfentrazone	14 bc	100 a	5 b	100 a
Trifloxysulfuron	0 d	100 a	0 c	100 a
Fomesafen	18 ab	100 a	5 b	100 a
Glufosinate	20 a	100 a	12 a	100 a
Mesotrione	10 c	100 a	1 bc	100 a
Linuron	0 d	100 a	6 b	100 a
Carfentrazone	23 a	100 a	10 a	100 a
Sulfentrazone+Clomazone[b]	0 d	100 a	0 c	100 a

[a] means followed by the same letter are not significant at $p \leq 0.05$.

[b] sulfentrazone and clomazone applied PRE-T only.

Table 9. Crop injury and Palmer amaranth control following before topping (BT) and after 1st harvest (AH) applications at the Lower Coastal Plain Research Station (LCPRS) and Upper Coastal Plain Research Station (UCPRS) in 2014.[a]

		LCPRS		**UCPRS**	
Herbicide	**Timing**	**Injury**	**Control**	**Injury**	**Control**
		---------------------%---------------------		---------------------%---------------------	
S-metolachlor	BT	0 a	100 a	0 b	88 a
S-metolachlor	AH	0 a	100 a	0 b	89 a
Sulfentrazone	BT	0 a	100 a	0 b	96 a
Sulfentrazone	AH	0 a	100 a	0 b	98 a
Trifloxysulfuron	BT	0 a	100 a	0 b	97 a
Trifloxysulfuron	AH	0 a	100 a	0 b	91 a
Fomesafen	BT	0 a	100 a	0 b	94 a
Fomesafen	AH	0 a	100 a	0 b	96 a
Glufosinate	BT	0 a	100 a	0 b	97 a
Glufosinate	AH	0 a	100 a	0 b	98 a
Mesotrione	BT	0 a	100 a	13 a	99 a
Mesotrione	AH	0 a	100 a	0 b	94 a
Linuron	BT	0 a	100 a	0 b	99 a
Linuron	AH	0 a	100 a	0 b	98 a
Carfentrazone	BT	0 a	100 a	0 b	95 a
Carfentrazone	AH	0 a	100 a	0 b	98 a
Sulfentrazone+Clomazone	PRE-T	0 a	100 a	0 b	98 a

[a] means followed by the same letter are not significant at $p \leq 0.05$.

[b] sulfentrazone and clomazone applied PRE-T only.

Table 10. Crop injury and Palmer amaranth control following before topping (BT) and after 1st harvest (AH) applications at the Lower Coastal Plain Research Station (LCPRS) and Upper Coastal Plain Research Station (UCPRS) in 2015.[a]

		LCPRS		UCPRS	
Herbicide	**Timing**	**Injury**	**Control**	**Injury**	**Control**
		---------------%	-------------------	------------ ---%	-----------------
S-metolachlor	BT	0 b	100 a	0 c	80 fg
S-metolachlor	AH	0 b	100 a	0 c	81 efg
Sulfentrazone	BT	0 b	100 a	0 c	100 a
Sulfentrazone	AH	0 b	100 a	0 c	96 abc
Trifloxysulfuron	BT	0 b	100 a	0 c	90 b-e
Trifloxysulfuron	AH	0 b	100 a	0 c	75 g
Fomesafen	BT	0 b	100 a	0 c	97 ab
Fomesafen	AH	0 b	100 a	0 c	93 a-d
Glufosinate	BT	0 b	100 a	0 c	99 a
Glufosinate	AH	0 b	100 a	3 c	95 abc
Mesotrione	BT	4 a	100 a	25 a	92 a-d
Mesotrione	AH	0 b	100 a	0 c	86 def
Linuron	BT	0 b	100 a	12 b	100 a
Linuron	AH	0 b	100 a	1 c	89 b-f
Carfentrazone	BT	0 b	100 a	0 c	94 a-d
Carfentrazone	AH	0 b	100 a	0 c	89 b-f
Sulfentrazone+Clomazone	PRE-T	0 b	100 a	0 c	88 c-f

[a] means followed by the same letter are not significant at $p \leq 0.05$.
[b] sulfentrazone and clomazone applied PRE-T only.

Table 11. Crop injury and Palmer amaranth control following before topping (BT) and after 1st harvest (AH) applications at the Lower Coastal Plain Research Station (LCPRS) and Upper Coastal Plain Research Station (UCPRS) in 2016.[a]

		LCPRS		UCPRS	
Herbicide	**Timing**	**Injury**	**Control**	**Injury**	**Control**
		--------------%	--------------------	---------------%	------------------
S-metolachlor	BT	0 c	100 a	0 b	99 a
S-metolachlor	AH	0 c	99 a	0 b	98 a
Sulfentrazone	BT	0 c	100 a	0 b	99 a
Sulfentrazone	AH	1 c	99 a	0 b	96 a
Trifloxysulfuron	BT	0 c	100 a	0 b	98 a
Trifloxysulfuron	AH	0 c	100 a	0 b	96 a
Fomesafen	BT	0 c	100 a	0 b	100 a
Fomesafen	AH	1 c	99 a	1 b	99 a
Glufosinate	BT	0 c	100 a	0 b	98 a
Glufosinate	AH	3 c	100 a	1 b	100 a
Mesotrione	BT	16 b	100 a	5 b	100 a
Mesotrione	AH	0 c	100 a	2 b	98 a
Linuron	BT	53 a	100 a	13 a	99 a
Linuron	AH	5 c	100 a	3 b	100 a
Carfentrazone	BT	0 c	100 a	0 b	94 a
Carfentrazone	AH	3 c	100 a	0 b	99 a
Sulfentrazone+Clomazone	PRE-T	0 c	100 a	0 b	95 a

[a] means followed by the same letter are not significant at $p \leq 0.05$.

[b] sulfentrazone and clomazone applied PRE-T only.

Table 12. Leaf yield, quality, value, and chemistry as influenced by herbicide application. Data are pooled across all environments with the exception of LCPRS 2015.[a]

Treatment	Timing	Yield	Quality	Value	Total Alkaloids	Reducing Sugars
		kg/ha		$/ha	----------------%	------------------
S-metolachlor	BT	3,080 a	82 a	11,445 a	2.45 a	16.4 a-d
S-metolachlor	AH	3,070 a	83 a	11,546 a	2.40 a	16.1 bcd
Sulfentrazone	BT	2,990 a	81 a	11,075 a	2.34 a	17.2 ab
Sulfentrazone	AH	3,150 a	83 a	11,978 a	2.37 a	16.4 a-d
Trifloxysulfuron	BT	3,200 a	83 a	12,332 a	2.44 a	16.6 a-d
Trifloxysulfuron	AH	3,020 a	82 a	11,074 a	2.47 a	16.2 a-d
Fomesafen	BT	3,020 a	83 a	11,524 a	2.52 a	16.6 a-d
Fomesafen	AH	2,980 a	83 a	11,272 a	2.36 a	16.7 a-d
Glufosinate	BT	3,020 a	81 a	11,250 a	2.33 a	16.6 a-d
Glufosinate	AH	3,190 a	82 a	11,963 a	2.47 a	16.8 abc
Mesotrione	BT	2,980 a	83 a	11,200 a	2.54 a	15.5 d
Mesotrione	AH	3,140 a	83 a	11,883 a	2.47 a	16.6 a-d
Linuron	BT	2,990 a	83 a	11,518 a	2.66 a	13.1 e
Linuron	AH	3,100 a	83 a	11,764 a	2.47 a	16.2 a-d
Carfentrazone	BT	2,880 a	81 a	10,899 a	2.49 a	15.9 cd
Carfentrazone	AH	3,100 a	83 a	11,858 a	2.48 a	17.0 abc
Sulfentrazone+Clomazone[b]	PRE-T	3,230 a	82 a	11,927 a	2.45 a	17.4 a

[a] means followed by the same letter are not significant at $p \leq 0.05$.
[b] sulfentrazone and clomazone applied PRE-T only.

Table 13. Leaf yield, quality, value, and chemistry as influenced by herbicide application at LCPRS in 2015.[a]

Treatment	Timing	Yield	Quality	Value	Total Alkaloids	Reducing Sugars
		kg/ha		$/ha	-------------%	------------------
S-metolachlor	BT	3,400 abc	87 a	13,681abc	1.72 a	19.5 c
S-metolachlor	AH	3,450 ab	88 a	14,203 ab	1.97 a	19.5 c
Sulfentrazone	BT	2,890 def	88 a	11,912 cd	1.59 a	20.4 abc
Sulfentrazone	AH	3,690 a	89 a	15,324 a	1.71 a	21.4 abc
Trifloxysulfuron	BT	3,150 bcd	89 a	13,088 bc	1.76 a	22.1 a
Trifloxysulfuron	AH	3,300 abcd	88 a	13,601 abc	1.61 a	19.7 bc
Fomesafen	BT	3,330 abcd	88 a	13,617 abc	1.79 a	20.8 abc
Fomesafen	AH	3,120 bcd	87 a	12,571 bcd	1.66 a	22.5 a
Glufosinate	BT	3,000 cdef	89 a	12,345 bcd	1.72 a	22.6 a
Glufosinate	AH	3,110 bcde	88 a	12,728 bc	1.71 a	21.1 abc
Mesotrione	BT	3,230 bcd	87 a	13,118 bc	1.67 a	21.9 ab
Mesotrione	AH	3,090 bcde	86 a	12,330 bcd	1.70 a	21.7 abc
Linuron	BT	2,630 f	87 a	10,662 d	1.91 a	16.6 d
Linuron	AH	3,130 bcd	89 a	12,918 bc	1.64 a	21.3 abc
Carfentrazone	BT	3,180 bcd	89 a	13,126 bc	1.79 a	20.4 abc
Carfentrazone	AH	3,370 abc	87 a	13,633 abc	1.70 a	22.6 a
Sulfentrazone+Clomazone[b]	PRE-T	2,670 ef	88 a	10,779 d	1.54 a	21.2 abc

[a] means followed by the same letter are not significant at $p \leq 0.05$.
[b] sulfentrazone and clomazone applied PRE-T only.

Table 14. Rotational restrictions for various field crops following late application in tobacco.

Herbicide	Small Grains	Soybean	Corn	Cotton	Peanut	Sweet Potato
Dual Magnum	4.5 months	None	None	None	None	60 days
Spartan	4 months*	None	10 months	18 months	12 months	12 months
Envoke	3 months*	7 months	7 months	7 months	7 months	18 months**
Reflex	4 months	None	10 months	None	4 months	12 months
Liberty	70 days	None	None	None	180 days	70 days***
Callisto	4 months	10 months	None	10 months	10 months	18 months
Linex	4 months	None	None	None	4 months	4 months
Aim	None	None	None	None	None	None
Poast	None	None	None	None	None	None

*Winter Wheat only

**Conduct field bioassay due to data being unavailable

***Includes root and tuber vegetables

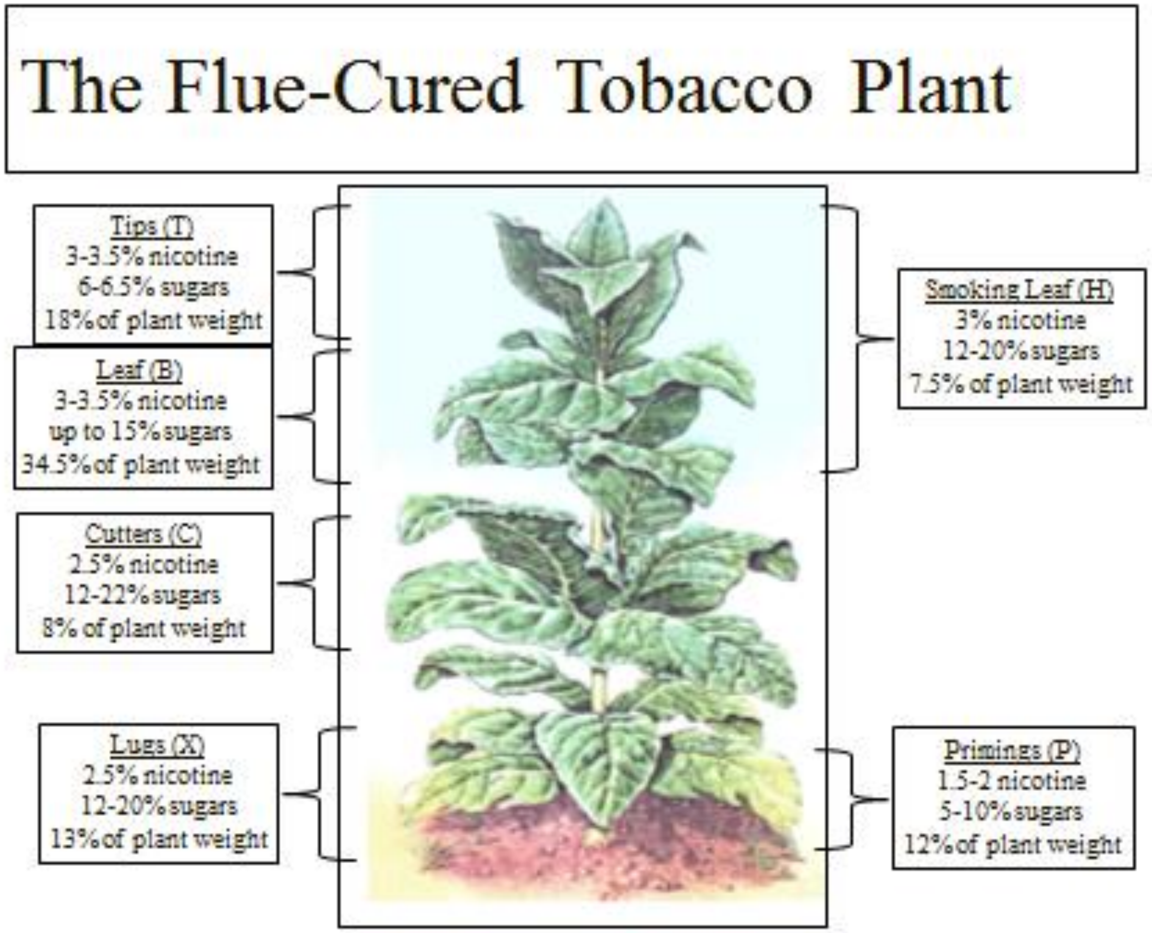

Figure 1. Characteristics of tobacco leaves based on stalk position (2017 Flue-Cured Tobacco Information, NCSU)