ABSTRACT

MARBURGER, ETHAN LEE. Field Evaluation of Condensed Quebracho Tannins (CQT) as a White-Tailed Deer Repellent for Soybeans. (Under the direction of Dr. Christopher S. DePerno).

In the United States, white-tailed deer (*Odocoileus virginianus*) and other ungulates are responsible for millions of dollars in annual agricultural damages, with crop damage posing a significant challenge to producers. While chemical and physical deterrents exist, many are ineffective, lack empirical evidence, and are impractical for large-scale use. Commercially available and commonly used in ruminant feeding trials, condensed quebracho tannins (CQT) are a naturally occurring secondary metabolite used by plants as a defense mechanism against foraging. Previous research determined that CQT negatively influenced intake rate and probability of consumption in captive white-tailed deer. Our objectives were to evaluate the efficacy of CQT sprayed on soybeans as a white-tailed deer repellent in a natural field setting near Black Creek, North Carolina, USA. Our experimental design consisted of 20 0.2-hectare plots, randomly assigned to either a treatment group (n = 10) or a control group (n = 10). During the growing season, treated fields received a single application of a solution containing 10% concentration of CQT and water at a carrier volume of 37.8 liters per acre. We placed camera traps in each plot to document white-tailed deer presence and foraging behavior and conducted weekly measurements of soybean height and browsing damage during the early growth stages. Results indicate that a single application of CQT modestly reduced white-tailed deer browsing on soybeans in an agricultural field setting with moderate to high deer densities. Treated plots experienced a statistically significant reduction in browsing (~72.9 percent) compared to control plots, particularly during the second to fourth weeks post-application. Soybean plants in treated plots displayed growth patterns more similar to those protected in enclosures, especially during the early weeks of the study, suggesting short-term suppression of browsing pressure. However,

treatment effects diminished over time, and soybean yield estimates were similar between treated and control plots. Additionally, no significant differences in observed deer feeding behavior were detected across treatment types, indicating that a single application of CQT may not be sufficient to establish lasting avoidance behavior or impact yield under field conditions. The limited long-term effectiveness of a single application may be attributed to factors such as CQT degradation, application method, and variability in deer behavior. Notably, environmental exposure and new plant growth appeared to reduce the repellent's visibility and potential efficacy after two weeks. These results suggest that CQT can influence deer behavior in the short term, but sustained reductions in browsing may require repeated applications, higher concentrations, or complementary deterrent strategies. Future research should explore more frequent or targeted applications, such as along field edges or high-depredation zones, alternative delivery systems to maximize contact with treated plants, and integration with broader management strategies. Additionally, evaluating CQT efficacy in small-scale, high-value cropping systems such as nurseries or specialty agriculture could offer further insight into its practical value as a commercial deer repellent.

Field Evaluation of Condensed Quebracho Tannins (CQT) as a White-Tailed Deer Repellent for Soybeans.

by
Ethan Lee Marburger

A thesis submitted to the Graduate Faculty of
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APPROVED BY:

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DEDICATION

I dedicate this thesis to my partner Annie and our dog Harley (aka The Ween). Over the past three years Annie has stood by me through sleepless nights and copious amounts of stress. Her unwavering love, support, and motivation has propelled me to face the unknown and follow my dreams. Unknowingly, Harley has provided the emotional support needed to finish my Master's degree. I am blessed and forever grateful to call them my family.

BIOGRAPHY

Ethan Lee Marburger was born in New Prague, Minnesota but raised in the hilltop community of Sherrill, Iowa. He grew up alongside his sister, Elaina, two step-siblings, Sam and Joyce, and parents, Becky and Joe. During the summers, he would return to Minnesota to spend time with his father, Bob. He developed a love of wildlife at a young age because of his continuous time spent outdoors. He continued to pursue his passion at the University of Northern Iowa where he studied Biology, further connecting with the natural world. After graduating from Northern Iowa (2020), he left the field to pursue other interests and reconnect with family. After two years, his desire to work with and conserve wildlife reignited his passion and he began his journey seeking higher education to better serve the natural world. His journey led him to North Carolina State University where he majored in Fisheries, Wildlife, and Conservation Biology to obtain his Masters of Science degree (2025). Throughout the years, he gained a plethora of experience, made lasting connections, and found the love of his life. His journey continues as he seeks to expand his horizons with a doctoral degree. He cannot wait to see what is in store for him next.

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CHAPTER 1

ABSTRACT

In the United States, white-tailed deer (*Odocoileus virginianus*) and other ungulates are responsible for millions of dollars in annual agricultural damages, with crop damage posing a significant challenge to producers. While chemical and physical deterrents exist, many are ineffective, lack empirical evidence, and are impractical for large-scale use. Commercially available and commonly used in ruminant feeding trials, condensed quebracho tannins (CQT) are a naturally occurring secondary metabolite used by plants as a defense mechanism against foraging. Previous research determined that CQT negatively influenced intake rate and probability of consumption in captive white-tailed deer. Our objectives were to evaluate the efficacy of CQT sprayed on soybeans as a white-tailed deer repellent in a natural field setting near Black Creek, North Carolina, USA. Our experimental design consisted of 20 0.2-hectare plots, randomly assigned to either a treatment group (n = 10) or a control group (n = 10). During the growing season, treated fields received a single application of a solution containing 10% concentration of CQT and water at a carrier volume of 37.8 liters per acre. We placed camera traps in each plot to document white-tailed deer presence and foraging behavior and conducted weekly measurements of soybean height and browsing damage during the early growth stages. Results indicate that a single application of CQT modestly reduced white-tailed deer browsing on soybeans in an agricultural field setting with moderate to high deer densities. Treated plots experienced a statistically significant reduction in browsing (~72.9 percent) compared to control plots, particularly during the second to fourth weeks post-application. Soybean plants in treated plots displayed growth patterns more similar to those protected in enclosures, especially during the early weeks of the study, suggesting short-term suppression of browsing pressure. However, treatment effects diminished over time, and soybean yield estimates were similar between treated and control plots. Additionally, no significant differences in observed deer feeding behavior were detected across treatment types, indicating that a single application of CQT may not be sufficient to establish lasting avoidance behavior or impact yield under field conditions. The limited long-term effectiveness of a single application may be attributed to factors such as CQT degradation, application method, and variability in deer behavior. Notably, environmental exposure and new plant growth appeared to reduce the repellent's visibility and potential efficacy after two weeks. These results suggest that CQT can influence deer behavior in the short term, but sustained reductions in browsing may require repeated applications, higher concentrations, or complementary deterrent strategies. Future research should explore more frequent or targeted applications, such as along field edges or high-depredation zones, alternative delivery systems to maximize contact with treated plants, and integration with broader management strategies. Additionally, evaluating CQT efficacy in small-scale, high-value cropping systems such as nurseries or specialty agriculture could offer further insight into its practical value as a commercial deer repellent.

INTRODUCTION

Crop losses due to wildlife damage are a significant concern for agriculture producers in the United States. The National Agricultural Statistics Service (2002) reported that crop losses to wildlife totaled US$619 million with 48% of agricultural operations reporting wildlife damage. Further, Conover et al. (2018) determined that white-tailed deer (*Odocoileus virginianus*: hereafter deer) are responsible for a majority of the agriculture damage resulting in an annual cost exceeding US$100 million (Conover 2002). In the southeastern United States crop depredation from deer caused some agricultural producers to cease soybean production (Wallace et al. 1996). On a farm in southwestern Ohio, USA Begley-Miller and Cady (2015) reported 43 percent income loss to deer from soybean depredation. These economic losses highlight the need for effective mitigation strategies. Hence, many producers have begun using deterrents to reduce browsing pressure and increase crop yields.

In addition to row crops, deterrents have long been used to protect nurseries and ornamental plantings from deer browsing (Conover 1984, Williams and Ward 2010). Effective methods to reduce deer damage include lethal control and physical exclusion (Walter et al. 2010). While lethal control methods may be effective, they are often restricted in urban areas and face public opposition (DeNicola et al. 1997, Walter et al. 2010). Wildlife agencies may issue depredation permits to lethally remove animals causing damage, but non-lethal methods are often preferred (Johnson et al. 2014). Fencing is a widely employed non-lethal method for reducing crop damage by deer, though its effectiveness depends on design and cost (Hildreth et al. 2012). Initial fencing costs can range from <US$2.00/m to US$20.00/m with additional maintenance and replacement costs (VerCauteren et al. 2006). As opposed to lethal control and fencing, repellents are non-lethal chemicals that are applied on or near vegetation to deter browsing (Conover 1984). Chemical repellents are generally sorted into four categories: taste, conditioned aversion, pain, and fear (Mason 1997, DeNicola et al. 2000, Wagner and Nolte 2001). Over time, consumption of treated plants can lead deer to associate the resulting distress with the vegetation ultimately reducing browsing impacts (Ward and Williams 2010).

Plants have evolved secondary metabolites as a defense mechanism against damage from herbivores and microbial pathogens (Wink 1988). Well known secondary metabolites are soluble phenolics known as tannins (Swain 1997). When tannins are consumed, free phenolic groups bind and form strong hydrogen bonds with dietary proteins, polymers (i.e. cellulose, hemicellulose, and pectin), and minerals resulting in increased nitrogen loss from reduced protein and cell wall digestion and reduced food intake (Robbins 1987, Butler 1989, Silanikove et al. 2001, McSweeney et al. 2001). Like other herbivores, deer have developed physiological mechanisms to overcome the adverse effects of tannins and other plant secondary metabolites (Austin et al. 1989). However, if detoxification processes are insufficient, excessive tannin consumption can lead to liver and kidney damage (McLeod 1974).

White-tailed deer have specialized liver adaptations for metabolizing secondary metabolites like tannins. Additionally, their saliva contains tannin-binding proteins which neutralize the effects of dietary tannins (Robbins et al. 1987, Robbins et al 1991). However, the tannin binding capacity of deer is not absolute and may be inefficient to bind or detoxify tannins of varying concentrations (Robbins et al 1991). Jones et al. (2010) examined the effect of condensed tannins on deer forage digestibility and noted that for every 1 percent increase in condensed tannin concentration, in vitro protein digestibility was reduced by 2.5 percent. Similarly, Cooper and Owen (1985) reported that ruminants rejected plants containing >5% concentration of condensed tannins. These results indicated that tannins have the potential to serve as a natural deterrent for reducing deer browsing.

Monteith et al. (2019) determined that an application of a solution containing 10% concentration of condensed quebracho tannins (henceforth known as CQT) when applied to soybeans repeatedly from mid-June to mid-August reduced the probability of deer feeding by 72 percent. Additionally, two days after application, the probability of deer avoiding a treated plot was 79% (Monteith et al. 2019). While the experiment was conducted in a laboratory setting, the results indicate that CQT may be an effective white-tailed deer depredation repellent. Therefore, to evaluate the efficacy of CQT in a natural field setting, we hypothesized that applying a 10% CQT solution to soybeans would provide a non-lethal method to reduce crop depredation by deer. Our objective was to evaluate the use of CQT in a field setting in North Carolina to determine the potential to reduce soybean depredation by deer.

STUDY AREA

To test the efficacy of our repellent, we conducted our study on a 6.6 km^2 privately owned area near Black Creek, North Carolina in Wilson County within the Coastal Plain region (Figure 1). The landscape is characterized by relatively flat terrain with gently rolling hills. Agriculture was the dominant land use type (55%), mainly producing soybeans, corn, and tobacco. Cattle ranches and hog farms accounted for 4% of the area. Roads consist of approximately 1% of the area. Forested land (40% of the area) is moderately fragmented while retaining connectivity. Dominant tree species include American White Oak (*Quercus alba*), American Red Oak (*Quercus rubra*), and Sweet Gum (*Liquidambar styraciflua*). Elevation averaged 32 m above sea level. The study site falls within the Contentnea Creek watershed, which received approximately 54.2 inches of rain in 2024. In 2024, the mean average temperature ranged from 72.9°F in May, 80.9°F in June, 82.5°F in July, 79.5°F in August, and 74.2°F in September, and 63.8°F in October (NOAA 2025). Deer density was approximately 31-40 per square mile (NC WRC 2020). Within the study area, we selected four no-till fields to house our experimental plots based on their proximity to woodlands and their prior depredation history. These fields were planted with soybeans in the previous year and corn two years prior.

MATERIALS AND METHODS

We conducted our study during the 2023 and 2024 summer growing seasons spanning from late May through October. Because CQT had yet to be tested in a field setting, the 2023 season served as a pilot year to refine methodology and site selection.

During the 2024 field season, we established twenty experimental plots across three privately owned agricultural fields. Plots were then randomly assigned into 2 groups: control (no application of tannins, n = 10) or treatment (application of CQT, n = 10). Experimental plots measured approximately 0.2 ha or 40 x 50 meters. Deer tend to browse near field edges particularly along areas adjacent to woodlands (Rogerson et al. 2014, Hinton et al. 2017, Monteith et al. 2019). To maximize the likelihood of observing browsing, we placed experimental plots along field edges adjacent to woodlands with a 5m buffer in between to avoid poor growth zones identified during the 2023 field season. We selected fields with relatively high-level browsing pressure from deer. Also, selected fields were irregularly shaped with ≥3 sides having adjacent woodlands. To evaluate the potential impact of CQT on crop yield, we conducted an additional test in a separate field with severe deer browsing history. Dubbed *the honey hole*, this field was irregularly shaped and completely encased by adjacent woodlands. Within the field, 8 alternating strips (50m x 5m) were established; treatment (n = 4) and control (n = 4). Soybeans were planted across all fields by the private landowner on May 23rd, 2024. See figure (1) for a visualization of our experimental design.

During the growing season, treatment plots received a single application of a 10% CQT solution mixed with water (**Appendices**). Based on Monteith et al. (2019), and consideration of real-world feasibility, we determined that a 10% concentration of CQT was optimal for balancing protection from browsing and economic viability. Deer browsing on soybeans is highest during the early growth stages, particularly during the cotyledon and early vegetative development (deClesta and Schwendeman 1978, Garrison and Lewis 1987, Colligan et al. 2011, Rodgerson et al. 2014). Losing more than 67% of leaves during early development significantly reduces soybean yield (Garrison and Lewis 1987). Because browsing is less detrimental to soybeans after the early growth stages (Colligan et al. 2011), we applied CQT during the second vegetative stage of soybean development when plant health and yield estimates are most affected by browsing pressure (Flyger and Thoerig 1962, deClesta and Schwendeman 1987, Hinton et al. 2017). We applied the CQT solution at a carrier volume of 93.5 liters per hectare using a John Deere 5090r tractor with a Reddick 3-point 45' boom sprayer.

Quantifying browsing

To measure physical differences in soybean development from browsing pressure or lack-there-of, we adapted methodology from Begley-Miller and Cady (2015). We recorded soybean plant height (cm) and browsing damage, defined as the proportion of petioles (leaf stems) with deer damage compared to the total number of petioles on the plant. We quantified measurements along a fixed transect spanning the width of each experimental plot. Observations during the 2023 field season identified a relationship between prolonged shading near woodlands and poor soybean growth. To minimize this impact and avoid shaded areas, we positioned transects in the middle of each plot. To further reduce potential errors from treatment application, we established a 5-meter buffer between the edges of the transects from the plot. Originally, we marked nine evenly spaced plants per transect which were measured weekly following repellent application. However, by the second week, some plants had died due to environmental or anthropogenic stressors. To ensure an adequate sample size, we marked additional plants, increasing the total to 17 individuals per transect in week two. Plants that died in subsequent weeks were not replaced and no further additions were incorporated into the study design. To assess potential soybean growth under minimal browsing pressure, we constructed $2m^2$ exclusion enclosures (**Appendices**) in each plot to protect a subset of plants from herbivory. These enclosures were positioned in the upper right-hand corner of each plot, along the plot border. Inside each enclosure, three plants were marked, and height and browsing damage were recorded weekly.

We documented deer presence using Recon Force Elite HP 5 cameras from Browning Trail Cameras. To minimize double counting the same individual, we used one camera per plot. We placed cameras centrally on the side of the plot adjacent to woodlands to maximize the likelihood of documenting browsing from deer (DeVault et al. 2007). We installed cameras at shoulder height to overcome potential line-of-sight issues from tall vegetation. To capture all passing individuals, we configured cameras to take 3-image-bursts with zero delay when triggered by movement (Hamel et al. 2013). Complications with camera functionality during the 2023 pilot season prompted implementation of weekly camera checks in 2024. We collected observations of feeding behavior for a period of four weeks.

To measure yield, we harvested 10m strips from experimental plots in the *Honey Hole* using a Wintersteiger Quantum Pro Small Plot Combine. Soybeans were harvested on October 31, 2024 to estimate yield differences. By applying a single application of 10% CQT concentration to a single field we aimed to reduce interfield biases, including biases associated with crop rotation history, pest management practices, or site-specific variability.

Statistical analysis

We investigated differences in soybean plant height, browsing damage, and white-tailed deer presence between treatment and control plots using linear regression models in R (version 4.4.3). To maintain consistency across analyses, we used mixed-effects models from the glmmTMB package for linear regression. Factors included in our models were CQT concentration (two levels: 0% control and 10% concentration of CQT), survey week after CQT application (four levels: weeks 1–4), enclosure (two levels: enclosed and open), plot (twenty levels: plots 1–20), and field (three levels: fields 1–3). Given the block-like-design of the experiment, field and plot were treated as nested random effects in linear regression models. Statistical significance level was set at alpha ≤ 0.05 for all models.

To analyze differences in soybean plant height, we fit a generalized mixed-effects model with a gamma distribution to account for the positive and continuous nature of the data. To compare heights from plants along transects to those in enclosures, we fit additional generalized mixed-effects models with gamma distributions corresponding to soybean heights in control and treatment plots.

To investigate differences in the proportion of browsing damage, we fit a generalized mixed-effects linear regression model with a binomial distribution. The response variable was specified as a two-column matrix, representing the counts of damaged and undamaged stems, respectively. This formulation allows the model to account for the number of successes (damaged stems) and failures (undamaged stems) in each observation.

To investigate differences in deer presence by treatment over time, we fit a mixed-effects linear regression model with a negative binomial distribution. Deer observations were aggregated as the total number of individuals observed per day and per plot.

To calculate yield (bushels/acre), we used weight and moisture data provided by the small harvest combine. We adjusted all yield measurements to the standard 13% moisture level. After calculating the dimensions of the harvested area per plot, we multiplied the weight in lbs by the area to get a weight by acre basis then divided the weight by 60 (average weight of a bushel of soybeans) to get bushels per acre. To investigate differences in estimated soybean yield between treatment and control plots, we fit the data to a one-way ANOVA model.

RESULTS

There was no significant difference in soybean height between treatment and control plots ($p = 0.438$; Figure 2). As expected, soybean height varied across survey weeks for all plots; however, there was no significant interaction between survey weeks and treatment (Table 1). Plants within protective exclusion enclosures were significantly taller than unprotected plants in both control ($p = <0.001$) and treatment ($p = 0.001$) plots (Table 2). Plants in treatment plots exhibited growth patterns more similar to enclosed plants than to those in open control plots (Figure 3). On a weekly basis, differences in height between protected plants inside enclosures and unprotected plants along transects were greater in control plots compared to treatment plots (Table 2).

Soybeans in control plots experienced significantly more browsing than in treatment plots ($p = 0.021$; Table 3). Based on an odds ratio, a single application of CQT resulted in a 72.9% reduction in the probability of deer browsing on soybean stems in treatment plots. Initially insignificant, the interaction between survey week and treatment increased so that by the second, third, and fourth weeks after repellent application, deer were 1.9 ($p = 0.186$), 2.6 ($p = 0.052$), and 3.0 ($p = 0.021$) times more likely to browse soybean stems in control plots than in treatment plots (Table 4).

There was no significant difference ($p = 0.129$) in the amount of deer observed displaying feeding behavior between treatment and control plots. On a weekly basis, the amount of deer exhibiting feeding behavior was similar between plots (Figure 4). Estimated soybean yield (bushels/acre) was similar between treatment and control plots ($p = 0.857$; Figure 5). The average yield estimate for soybeans in treatment plots was 60.61 bushels/acre, compared to 61.60 bushels/acre for control plots.

DISCUSSION

Monteith et al. (2019) reported that an application of CQT to manipulated soybeans plots resulted in a 72% reduction in feeding probability. The strong avoidance of CQT by deer in their experiment highlighted the potential of CQT as an effective strategy to deter white-tailed deer from feeding in areas prone to crop depredation (Monteith et al. 2019). Our results indicate that a single application of CQT modestly reduced white-tailed deer browsing by 72.9% during weeks two to four post-application. Treated plants showed short-term growth benefits similar to those in enclosures, but effects diminished over time, and yield remained similar across treatments. No significant differences in deer feeding behavior were observed, suggesting that one application is insufficient for lasting deterrence.

Begley-Miller and Cady (2015) determined that plants protected from browsing were significantly taller, likely contributing to increased above-ground biomass and yield. In our study, unprotected CQT-treated soybeans were taller than those in control plots and similar in height to protected plants the first two weeks of the study. In weeks three and four, soybean height was statistically different between unprotected transects and adjacent protected plants in treatment plots, suggesting that a single application of CQT can temporarily reduce but not eliminate browsing pressure.

Similar to Monteith et al. (2019), deer in our study were 72.9% less likely to browse soybeans in treatment plots. For CQT to be an effective repellent, it must elicit a negative foraging association that deters future consumption (Gillingham and Bunnell 1989). Monteith at el. (2019) reported that avoidance of CQT-treated plots increased over two consecutive days in feeding trials. In our study, we reported that plants in control plots were increasingly more likely to be browsed by deer over plants in treatment plots. The decrease in the probability of browsing in treatment plots indicates that CQT may elicit a negative foraging association and deter future consumption.

Notably, deer exhibited similar feeding behavior in treatment and control plots, further indicating that while CQT may influence browsing levels, a single application was not sufficient to alter deer feeding behavior significantly. While control plots experienced higher browsing rates later in the study compared to treatment plots, differences in browsing damage were not reflected in post-harvest estimates. Soybean yield estimates (bushels/acre) were similar between treatment and control plots, with control plots producing a slightly higher yield (~1.0 bushels/acre). This yield discrepancy may be partially attributed to intra-field plot locations, as three of the eight plots (one control and two treatment) were positioned in areas with high deer activities and bedding sites (E. Marburger, personal observations). Additionally, we only quantified soybean damage for four weeks during the growing season, yield estimates may have been affected by deer browsing occurring after our study.

Unlike the methodology employed by Monteith et al. (2019), which used manipulated food plots and captive deer, our study was conducted in an agricultural field setting with a moderate to high-density deer population. While a single application of CQT was able to reduce the probability of deer browsing in treatment plots, it may not be sufficient to encounter the majority of individuals in that area. If deer do not rapidly consume CQT-treated plants, negative foraging association and therefore repellent efficiency may diminish as a result of changing plant morphology and environmental variables. In areas with high deer densities, avoidance of feeding from only a subset of individuals may not be enough to significantly influence yield estimates.

Unlike controlled laboratory settings, field trials introduce environmental variables and application constraints that influence repellent efficacy. Evidence of CQT on plants persisted for approximately two weeks post-application. After this period, new plant growth and environmental conditions diminished the visual presence of CQT, suggesting that CQT efficacy is strongest within the first two weeks post-application. In areas with similar moderate–high deer densities, weekly application of CQT, particularly along field edges where browsing is most concentrated, may be necessary for the majority of deer to encounter, consume, and elicit a negative foraging association with CQT-treated plants. Application timing is also critical as browsing has the greatest impact on soybean morphology and yield during early vegetative growth stages (Garrison and Lewis 1987, DeVault et al. 2007, Walter et al. 2010, Colligan et al. 2011, Delger et al. 2011, Rogerson et al. 2014, Hinton et al. 2017, and Monteith et al. 2019).

Our results, in conjunction with Monteith et al. (2019) indicate that CQT may be an effective deer repellent under specific conditions. However, for large-scale agricultural applications, future research should investigate scenarios with increased CQT application frequencies as well as alternative repellent application methods (i.e. direct or shield spraying) to reduce product waste on bare ground and increase cost-effectiveness. Additionally, evaluating CQT efficacy in high-value cropping systems such as nurseries could provide further insight into its broader applicability as a commercial deer repellent.

MANAGEMENT IMPLICATIONS

Based on a 10% CQT concentration and the application rate used in our study (93.5 L per hectare) the estimated cost of using CQT as a deer repellent was ~US$96.88/ha. In the United States, the average harvested soybean acreage is 297 acres per farm (USDA 2017) meaning that applying CQT across an entire farm would be $11,644 USD. Our results indicate that in areas with moderate to high deer densities producers experiencing significant browsing pressure should apply CQT at least twice over the span of a two-week period. In New Jersey, USA where annual losses to white-tailed deer average $51,852 per farm (Paulin et al. 2022), the potential benefits of repeated CQT application may justify the cost. At this frequency, CQT may remain on plants long enough for deer to consume treated vegetation, experience feeding distress, and form a negative foraging association, maintaining the repellent effectiveness reported in this study and by Monteith et al. (2019). To reduce costs, farmers could target CQT applications along field borders or areas with the highest depredation pressure, allowing for more frequent treatments while minimizing overall repellent use. Combining CQT application with broader management strategies, such as a hunting lease, may improve repellent success while maximizing profitability. Additionally, CQT may prove particularly effective in small-scale agricultural operations, gardens, or nurseries where higher frequency applications are more cost-effective and efficient.

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Table 1. Summary of mixed-effects linear regression model with a gamma distribution (link = “log”) used to investigate differences in soybean height (cm) for plants from experimental plots in Wilson County, North Carolina, USA, 2024. Week after application is abbreviated as WAT. Asterisks (*) denote statistical significance at α = 0.05.

Predictors	*Estimate*	*Std. Error*	*CI (95%)*	*P-value*
(Intercept)	2.630	0.111	2.412 – 2.848	<0.001*
Treatment [1]	0.042	0.054	-0.064 – 0.149	0.438
WAT [2]	0.086	0.032	0.023 – 0.150	0.008*
WAT [3]	0.324	0.033	0.260 – 0.387	<0.001*
WAT [4]	0.629	0.033	0.565 – 0.693	<0.001*
Treatment [1] × WAT [2]	0.034	0.046	-0.056 – 0.124	0.455
Treatment [1] × WAT [3]	0.006	0.046	-0.084 – 0.097	0.890
Treatment [1] × WAT [4]	-0.001	0.046	-0.092 – 0.090	0.987

Table 2. Summary of mixed-effects linear regression models with gamma distributions (link = “log”) used to investigate differences in soybean height (cm) between unprotected plants and protected plants from (a) control plots and (b) treatment plots in Wilson County, North Carolina, USA, 2024. Week after application is abbreviated as WAT. Asterisks (*) denote statistical significance at α = 0.05.

a.

Predictors	*Estimate*	*Std. Error*	*CI (95%)*	*P-value*
(Intercept)	2.630	0.096	2.443 – 2.820	<0.001*
Enclosure [1]	0.211	0.051	0.111 – 0.311	<0.001*
WAT [2]	0.087	0.032	0.025 – 0.150	0.005*
WAT [3]	0.326	0.032	0.264 – 0.388	<0.001*
WAT [4]	0.630	0.032	0.567 – 0.693	<0.001*
Enclosure [1] × WAT [2]	0.172	0.070	0.034 – 0.309	0.014*
Enclosure [1] × WAT [3]	0.183	0.070	0.045 – 0.321	0.009*
Enclosure [1] × WAT [4]	0.213	0.070	0.074 – 0.349	0.002*

b.

Predictors	*Estimate*	*Std. Error*	*CI (95%)*	*P-value*
(Intercept)	2.684	0.100	2.487 – 2.880	<0.001*
Enclosure [1]	0.160	0.051	0.060 – 0.261	0.001*
WAT [2]	0.121	0.032	0.059 – 0.183	<0.001*
WAT [3]	0.331	0.032	0.268 – 0.393	<0.001*
WAT [4]	0.629	0.032	0.566 – 0.692	<0.001*
Enclosure [1] × WAT [2]	0.094	0.070	-0.043 – 0.232	0.179
Enclosure [1] × WAT [3]	0.148	0.070	0.010 – 0.286	0.035*
Enclosure [1] × WAT [4]	0.148	0.070	0.009 – 0.286	0.036*

Table 3. Summary of mixed-effects linear regression model with a binomial distribution to investigate differences in the proportion of browsing damage for plants from experimental plots in Wilson County, North Carolina, USA, 2024. Week after application is abbreviated as WAT. Asterisks (*) denote statistical significance at α = 0.05.

Predictors	*Estimate*	*Std. Error*	*CI (95%)*	*P-value*
(Intercept)	-3.209	0.334	-3.864 – -2.555	<0.001*
Treatment [1]	-1.305	0.564	-2.409 – 0.200	0.021*
WAT [2]	0.728	0.265	0.209 – 1.246	0.005*
WAT [3]	0.383	0.266	-0.138 – 0.904	0.149
WAT [4]	0.171	0.264	-0.346 – 0.688	0.517
Treatment [1] × WAT [2]	0.642	0.486	-0.310 – 1.595	0.186
Treatment [1] × WAT [3]	0.941	0.484	-0.007 – 1.889	0.052
Treatment [1] × WAT [4]	1.104	0.480	0.163 – 2.045	0.021*

Table 4. Odds ratios, CI (95%), and P-values for treatment main effect and treatment and WAT interactions from the mixed-effects linear regression model with a binomial distribution to investigate differences in the proportion of browsing damage for plants from experimental plots in Wilson County, North Carolina, USA, 2024. Week after application is abbreviated as WAT. Asterisks (*) denote statistical significance at α = 0.05.

Predictors	*Odds ratio*	*CI (95%)*	*P-value*
Treatment [1]	0.271	0.089 - 0.818	0.021*
Treatment [1] × WAT [2]	1.900	0.733 - 4.926	0.186
Treatment [1] × WAT [3]	2.567	0.992 - 6.618	0.052
Treatment [1] × WAT [4]	3.017	1.177 - 7.731	0.021*

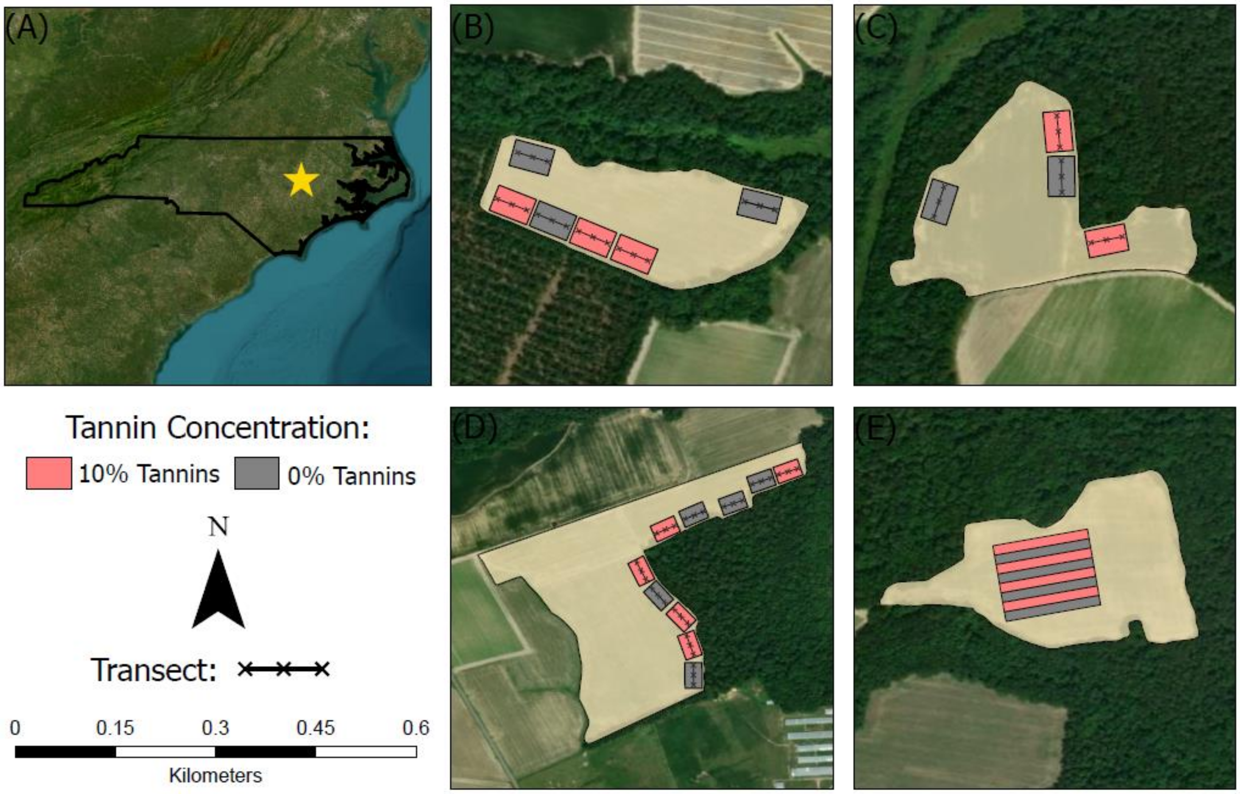

Figure 1. Experimental design of study sites across the sampling area in Wilson County, North Carolina, USA, 2024. Map frame (A) represents the relative area in North Carolina, USA where we conducted our study. Map frames (B), (C), and (D) represent experimental plots within fields used to assess the effects of the repellent on soybean height, browsing damage, and white-tailed deer presence in treatment plots (10% tannin concentration) and control plots (0% tannin concentration). Map frame (E) illustrates the experimental layout, in the *Honey Hole*, for estimating soybean yield among similar treatment and control plots.

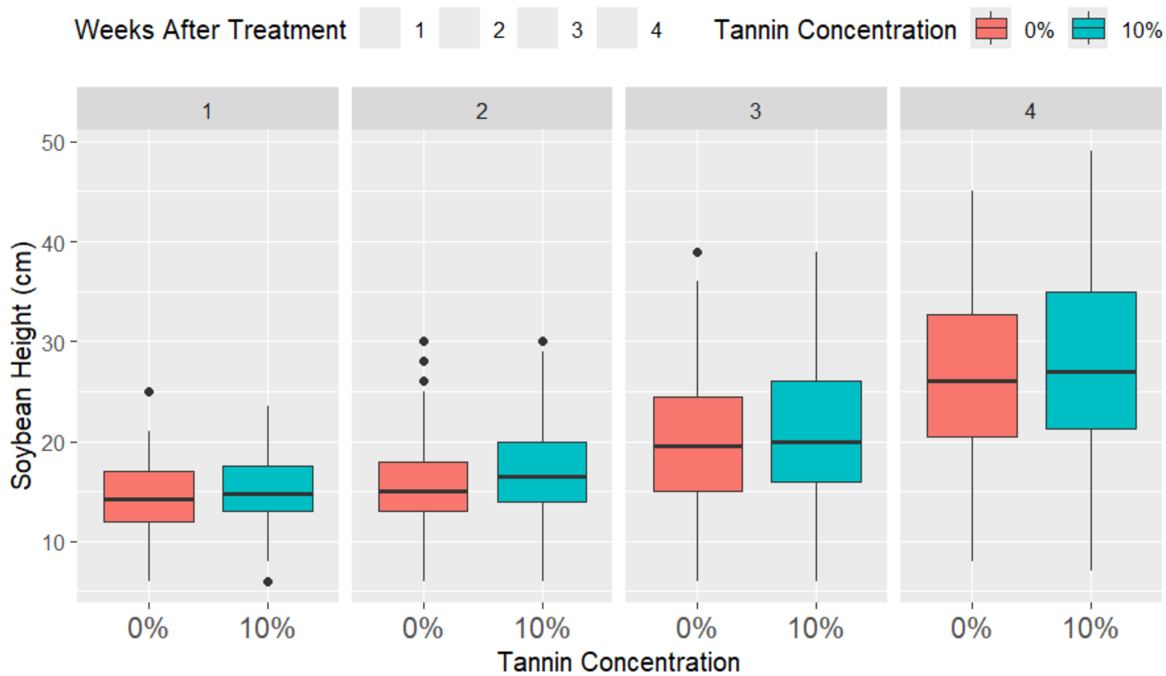

Figure 2. Distribution of soybean height (cm) by condensed quebracho tannin (CQT) concentrations (0% and 10%) over time from experimental plots in Wilson County, North Carolina, USA, 2024. CQT concentrations of 0% and 10% correspond to control and treatment plots. Height measurements were recorded weekly for four weeks.

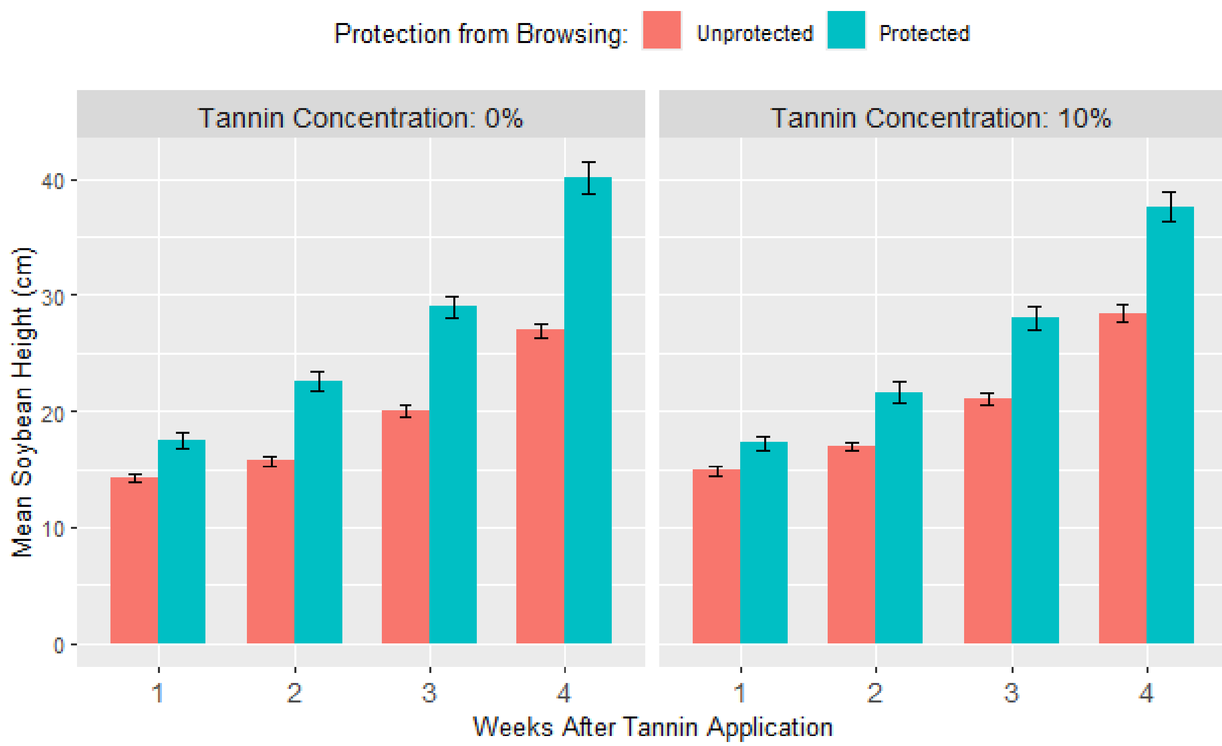

Figure 3. Mean soybean heights for plants unprotected from white-tailed deer browsing versus mean soybean heights for plants protected from browsing over time by condensed quebracho tannin (CQT) concentrations (0% and 10%) in Wilson County, North Carolina, USA, 2024. CQT concentrations of 0% and 10% correspond to control and treatment plots. Plants unprotected from browsing were from transects in experimental plots with varying levels of CQT concentration; while plants protected from browsing were from deer enclosures placed within experimental plots. Plants protected from browsing did not receive an application of CQT even if they were within treatment plots. Height measurements were recorded weekly for four weeks.

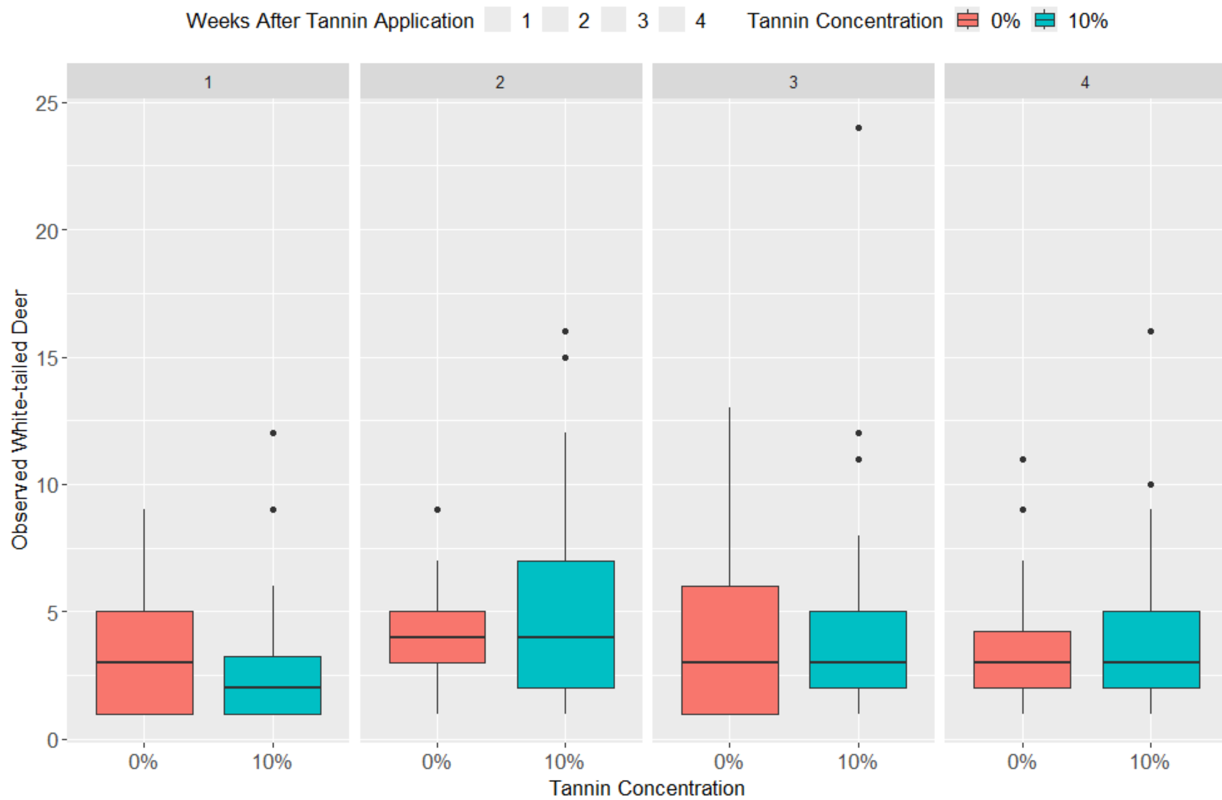

Figure 4. Distribution of deer observed exhibiting browsing behavior in experimental plots by condensed quebracho tannin (CQT) concentrations (0% and 10%) over time in Wilson County, North Carolina, USA, 2024. Deer presence and use was recorded for six weeks. CQT concentrations of 0% and 10% correspond to control and treatment plots.

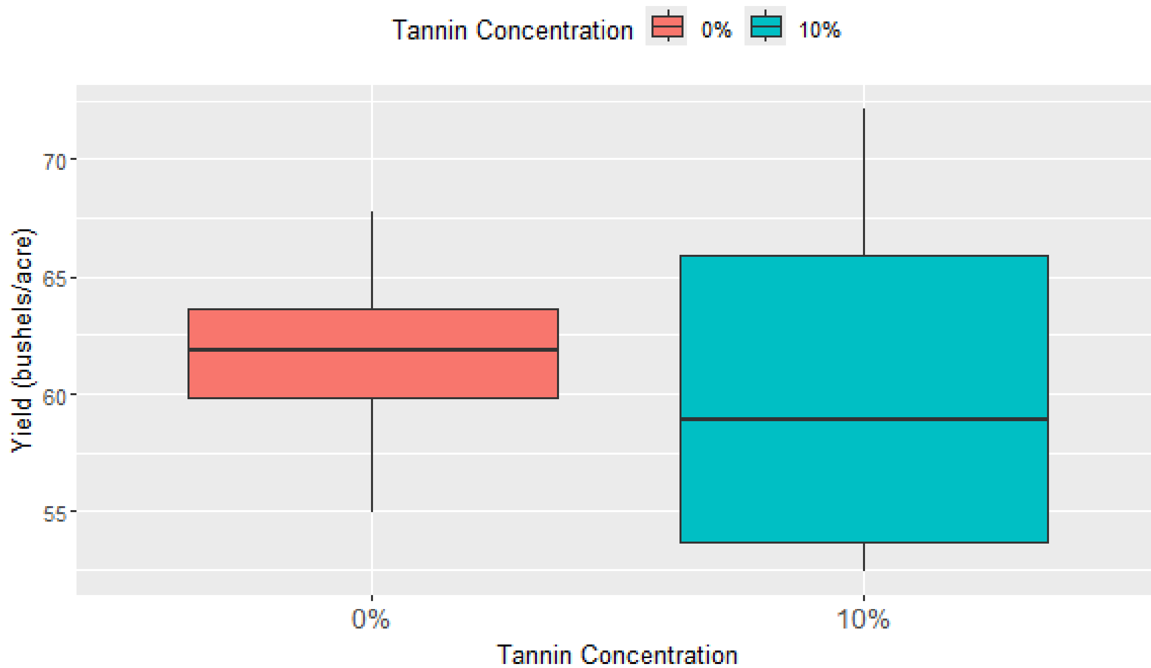

Figure 5. Distribution of yield (bushels/acre) estimates by condensed quebracho tannin (CQT) concentrations (0% and 10%) in experimental plots from "*The Honey Hole*" in Wilson County, North Carolina, USA, 2024. CQT concentrations of 0% and 10% correspond to control and treatment plots.

APPENDICES

Appendix 1. Storage, Handling, and Mixing Instructions for Condensed Quebracho Tannins for use as a Deer Repellent.

1.1 Condensed Quebracho Tannin Storage and Protection

1. Storage: Store condensed quebracho tannins in a cool and dry place.
2. Protection: Wear personal protective equipment (PPE) such as a dust mask, eye protection, and protective gloves be worn when handling dry powders.

1.2 Condensed Quebracho Tannin Mixing Instructions

1. Equipment: For easy transportation, use an IBC tank with a steel pallet. To mix the repellent, use a Marshalltown Eggbeater 30-in Steel Paddle Mixing Arm and a DEWALT 1/2-in Keyed Drill.
2. Water Addition: Fill the tank with water at the desired volume.
3. Incremental Mixing: Gradually combine condensed quebracho tannins with water in small increments, mixing intermittently.
4. Thorough Mixing: Mix well until the condensed tannin powder is no longer visible.
5. Paste Formation: Note that the initial mixture of condensed quebracho tannins and water may cause the tannin powder to form a thick paste, which may stick to the eggbeater.
6. Settling Period: Allow the mixed solution to sit for up to 24 hours with intermittent mixing to ensure the solution is completely soluble.

Appendix 2. Image depicting a white-tailed deer enclosure to protect plants from herbivory in each experimental plot.

Appendix 3. Linear Regression and ANOVA Model Tables.

3.1. Summary of a mixed-effects linear regression model using a negative binomial distribution to assess differences in white-tailed deer browsing behavior across experimental plots with varying condensed quebracho tannin (CQT) concentrations (0% and 10%) over time in Wilson County, North Carolina, USA, during the 2024 field season. Tannin concentrations of 0% and 10% represent control and treatment plots, respectively. Week after application is abbreviated as WAT. Asterisks (*) denote statistical significance at $\alpha = 0.05$.

Source	*Estimate*	*Std. Error*	*CI (95%)*	*P-value*
(Intercept)	1.215	0.189	0.844 – 1.586	<0.001*
Treatment [1]	-0.297	0.196	-0.681 – 0.086	0.129
WAT [2]	0.183	0.182	-0.174 – 0.539	0.316
WAT [3]	0.148	0.188	-0.220 – 0.517	0.430
WAT [4]	-0.024	0.201	-0.417 – 0.370	0.906
Treatment [1] × WAT [2]	0.415	0.250	-0.075 – 0.905	0.096
Treatment [1] × WAT [3]	0.434	0.264	-0.083 – 0.952	0.100
Treatment [1] × WAT [4]	0.446	0.269	-0.083 – 0.974	0.098

3.2. Summary of ANOVA model investigating differences yield (bushels/acre) estimates from experimental plots by condensed quebracho tannin (CQT) concentrations (0% and 10%) in Wilson County, North Carolina, USA, 2024. Tannin concentrations of 0% and 10% correspond to control and treatment plots.

Source	Df	SS	MS	F-value	Pr(>F)
Tannin Concentration	1	2.0	1.97	0.035	0.857
Residuals	6	335.5	55.92		