Optimizing Laser and Liquid Nitrogen Treatments for Weed Control in Turfgrass Systems

Juan Ramon Romero Cubas

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
in Life in Science in
Plant Pathology, Physiology, and Weed Science

Shawn D. Askew, Chair
David S. McCall
J. Michael Goatley

May 05, 2025
Blacksburg, Virginia

Keywords:
Organic weed control
Laser weed control
Cryogenic liquids

Optimizing Laser and Liquid Nitrogen Treatments for Weed Control in Turfgrass Systems.

Juan R. Romero

Academic Abstract

The increasing prevalence of herbicide-resistant weeds and growing environmental concerns surrounding synthetic pesticides are driving innovation in non-chemical weed control technologies. This research evaluated two emerging approaches based on the premise of machine-vision-based, individual-plant treatments to problematic turfgrass weeds: cryogenic liquid exposure and patterned laser energy. In the cryogenic study, a custom-built applicator was used to deliver precise doses of liquid nitrogen (LN) to individual plants of goosegrass (*Eleusine indica*) and annual bluegrass (*Poa annua*). Four field trials were conducted across two sites in Blacksburg, VA, testing seven LN doses (0–5.1 mL). LN reduced green cover rapidly (3 days after treatment) in both species, with 90% control achieved at ≥2.2 mL. Annual bluegrass responded consistently across trials, while goosegrass exhibited site-dependent recovery. In the laser study, a 10 W diode laser was used to treat four turf and weed species across varying pattern-averaged energy densities (PAED), pattern line spacings, and pass numbers to simulate systems where patterns of equidistant lines would be targeted to unwanted weeds in turf. A factorial design revealed that 4-mm line spacing improved control compared 1- or 2-mm line spacing, likely due to increased line-specific energy density. Bermudagrass (*Cynodon dactylon*) fully recovered from all treatments within 24 days, while creeping bentgrass (*Agrostis stolonifera*) had recovered less than 50%, emphasizing the need for accurate weed targeting systems. These results demonstrate the feasibility of LN and laser-based precision weed control in turfgrass systems and highlight the importance of dose optimization and spatial pattern design to balance efficacy with turfgrass safety. Future work should focus on integrating these tools with autonomous delivery platforms for scalable, selective weed management.

Optimizing Laser and Liquid Nitrogen Treatments for Weed Control in Turfgrass Systems.

Juan R. Romero

General Audience Abstract

As weeds develop mechanisms to survive herbicide treatments and public concern grows over the effects of chemical herbicides, the search for safer and more sustainable weed control methods becomes increasingly important—especially in areas like golf courses, sports fields, and lawns, where appearance and safety are critical. This project evaluated two innovative, non-chemical approaches: one using extreme cold (liquid nitrogen) and another using focused heat (a laser beam). The main target weeds included annual bluegrass, smooth crabgrass, and goosegrass, while common turfgrasses like bermudagrass and creeping bentgrass were tested for treatment safety. In the liquid nitrogen (LN) trials, a custom-built applicator delivered precise amounts of LN to individual weed plants. Across four field trials in Blacksburg, VA, seven doses ranging from 0 to 5.1 mL were applied. Both species showed a rapid decline in green cover within three days, and doses of 2.2 mL or more achieved over 90% control. Annual bluegrass responded consistently across locations, while goosegrass recovery varied depending on the site. The laser study used a 10-watt diode laser to apply energy in line patterns with varying energy levels, spacing, and number of passes. A 4-mm line spacing provided better weed control than narrower spacings, likely due to greater energy concentration per line. Bermudagrass recovered fully within 24 days, while creeping bentgrass recovered less than 50%, underscoring the need for precise targeting to avoid injury to desirable turf. Overall, the results demonstrate strong potential for LN and laser-based methods in selective, non-chemical weed control. Success depends on optimizing both dose and spatial pattern. Future work should focus on integrating these approaches with automated systems to enable efficient, large-scale implementation.

I dedicate this dissertation to my family, who have supported me in every single project over the last years: to my beloved wife, Maria Marcela, and to my daughters, Sofia and Camila.

ACKNOWLEDGEMENTS

I am sincerely grateful for the opportunity I had to spend two enriching years at Virginia Tech; this time truly changed my perspective on the world. First and foremost, I want to express my deepest appreciation for my major advisor, Dr. Shawn Askew. Even though I had no experience in turfgrass weed science, he believed in me and always provided support and guidance. I was fortunate to work alongside one of the brightest minds I have ever encountered. His support made me not only a better professional but also a better person. Many thanks to his wife, Whitnee Askew, who is an incredible thinker and always offers valuable advice for every situation. This gratitude is also extended to Drs. Mike Goatley and David McCall for being members of my graduate advisory committee. Their guidance and support have been invaluable throughout my journey, stimulating creative thoughts and insights across the discipline.

I would like to thank the folks at the Glade Road Research Facility and the Virginia Weed Team for their numerous support during my time at Virginia Tech. Additionally, I want to thank Drs. Michael Flessner and Jacob Barney for their rigorous training for the weed contest; it was a great experience that I will remember all my life. I also want to express my appreciation to all the graduate students with whom I interacted during my time here. The friendships we forged during weed team training, extension events, and academic meetings are truly cherished. I learned a great deal from each of you and was inspired by your passion and talent for weed and turfgrass science. This collective enthusiasm from all of you continually pushed me to improve; you showed me that hard work always pays off. I would like to acknowledge Daewon Koo, John Peppers, Navdeep Godara, Caleb Henderson, Aaron Tucker, Kevin Bamber, Eli Russell, Cynthia Sias, Suzannah Hale, Aman Jakhar, Jenna Beville, Wyatt Stutzman, Elisabeth Kitchin, and Ava Veith for their assistance and the cherished memories we created together. To the Bargmann Lab, Dr. Bastiaan Bargmann, Joseph Taylor, and Kelsey Reed, thank you for opening the first door at Virginia Tech.

I would like to express my deepest gratitude to my parents, Juan Ramon Romero and Nolvia Melanea Cubas, for their unwavering love and support. To my wife, Maria Morales, I am forever indebted to you. This journey would have been impossible without your constant support. Like a team, we navigated the complexities of married life, and you took care of every detail in our family, especially those concerning the education of our daughters, Sofia and Camila. I want to express my gratitude to my family in Honduras, Samuel, Maria, Nery, Fanny, Kevin, Jenssy, Logan, Mia, Grecia, Mario and the extended family, as they always cheer for my success. To my family in the US, Daniel, Claudia, Isaac, Alex, Ericka, Dieguito, Fredy, and Lila, thank you for opening your homes every time we needed assistance. Lastly, to my dear friends Hicsa, Paul, Armida, Marty, Arnel, Myleidi, Laura, Alice, Vladimir, Vanessa, Sofia, Bruce, Tony, and Ester for their kind words and support throughout this process.

ATTRIBUTIONS

Chapter II. A Targeted Application System for Evaluating Goosegrass and Annual Bluegrass Response to Liquid Nitrogen.

Juan R. Romero is a Turfgrass Weed Science Research Assistant in the School of Plant and Environmental Sciences at Virginia Tech. He assisted in experimental conceptualization, data collection, investigation, interpretation for the studies, statistical analysis, and manuscript draft preparation, as well as the first author for this chapter.

Navdeep Godara is a Ph.D. in Turfgrass Weed Science in the School of Plant and Environmental Sciences at Virginia Tech. He assisted with data collection, investigation, and critical edits of the paper.

Shawn D. Askew is a professor of Turfgrass Weed Science in the School of Plant and Environmental Sciences at Virginia Tech. He assisted with experimental conceptualization, investigation, and statistical analysis, as well as providing critical edits to the content of the written draft.

Chapter III. Response of Annual Bluegrass, Bermudagrass, Creeping Bentgrass, and Smooth Crabgrass to Laser Intensity Levels and Patterns.

Juan R. Romero is a Turfgrass Weed Science Research Assistant in the School of Plant and Environmental Sciences at Virginia Tech. He assisted in experimental conceptualization, data collection, investigation, interpretation for the studies, statistical analysis, and manuscript draft preparation, as well as the first author for this chapter.

Navdeep Godara is a Ph.D. in Turfgrass Weed Science in the School of Plant and Environmental Sciences at Virginia Tech. He assisted with data collection, investigation, and critical edits of the paper.

Shawn D. Askew is a professor of Turfgrass Weed Science in the School of Plant and Environmental Sciences at Virginia Tech. He assisted with experimental conceptualization, investigation, and statistical analysis, as well as providing critical edits to the content of the written draft.

TABLE OF CONTENTS

LIST OF TABLES

Chapter II. A Targeted Application System for Evaluating Goosegrass and Annual Bluegrass Response to Liquid Nitrogen.

Chapter III. Response of Annual Bluegrass, Bermudagrass, Creeping Bentgrass, and Smooth Crabgrass to Laser Intensity Levels and Patterns.

LIST OF FIGURES

Chapter II. A Targeted Application System for Evaluating Goosegrass and Annual Bluegrass Response to Liquid Nitrogen.

Chapter III. Response of Annual Bluegrass, Bermudagrass, Creeping Bentgrass, and Smooth Crabgrass to Laser Intensity Levels and Patterns.

Chapter I. Literature Review

Characterizing weed control in turf and the need for alternatives

Effective weed control is a cornerstone of turfgrass management, ensuring the high-quality appearance and playability that homeowners, groundskeepers, and sports managers demand (McCarty et al. 1994; McElroy and Martins 2013). Historically, synthetic herbicides have been the primary tool for achieving effective weed control due to their ease of application and cost-effectiveness on a large scale. However, recent shifts in public perception have brought new challenges and responsibilities for turf managers and practitioners seeking to maintain weed-free turf areas (Barzman and Dachbrodt-Saaydeh 2011; Golf Sustainable 2024).

One of the primary concerns among many communities is human and environmental safety, especially regarding children who spend considerable time playing on turf. Although synthetic herbicides are regulated and generally deemed safe when used correctly, recent litigation regarding glyphosate has raised a movement of environmental organizations that have increasingly called for restrictions or pesticide bans (Donley 2019). Although herbicides like synthetic auxins can reduce harmful insecticide exposure to pollinators, their use could lead to a reduction in food resources for them. In light of these concerns, many homeowners and turf managers are exploring alternative approaches that can reduce the reliance on synthetic herbicides while still ensuring effective weed control (Godara et al. 2023; Bush and Salamanca 2024).

Another driver behind the quest for additional management strategies is the emergence of herbicide-resistant weed populations (Brosman et al. 2020). Over time, repeated use of the same herbicide modes of action (MOA) have fostered weeds that tolerate or survive treatments

designed to eliminate them. The growing prevalence of herbicide resistance in problematic species like annual bluegrass (*Poa annua* L.) and goosegrass (*Eleusine indica* L. Gaertn.) has challenged the efficacy of traditional synthetic herbicides in turfgrass. This resistance not only limits the effectiveness of once-affordable herbicides but also places a greater burden on turf managers to rotate MOAs or integrate other more time-consuming weed control methods (McCurdy et al. 2023).

In response, turfgrass researchers and industry professionals are working to develop and refine alternative solutions. Recent studies have investigated 14 different non-synthetic herbicides, which show promise as eco-friendly herbicides; however, these products fail to provide long-term weed control (Askew et al. 2024). McElroy and Bhowmik (2013) also advocate for improved cultural practices, such as optimized mowing and fertilization techniques to reduce weed pressure naturally. Mechanical weed removal methods, precision application technologies like targeted spraying, heat (laser) or cryogenic treatments are increasingly being explored as supplementary tools to enhance weed control. These strategies do not necessarily replace synthetic herbicides altogether; rather, they can supplement or partially replace them, creating integrated management systems that address public safety concerns and resistance challenges simultaneously (Andreasen et al. 2024; Romero and Askew 2023).

Organic herbicides cost and associated risk

Organic herbicides are often perceived as more environmentally friendly options for weed control, yet many issues persist regarding their effectiveness, costs, and application methods. In a recent study, Askew et al. (2024) showed that products like Green Gobbler (containing 40% acetic acid) could suppress annual bluegrass when applied at 299 kg ai ha^{-1}. However, this control lasted only around 16 days, whereas synthetic herbicides such as glyphosate or

glufosinate maintained over 80% control for nearly three months under similar conditions. The high application rates of organic herbicides also translate to greater environmental load, undermining their perceived eco-friendliness (Dayan et al. 2009). Moreover, cost becomes a constraint, particularly in large, public areas like golf courses, parks, and sports fields, where budget restrictions already pose challenges. By comparison, the cost of treating one hectare with Green Gobbler can exceed $12,000, while a glyphosate-based solution may cost as little as $10 per hectare. Frequent reapplication also drives up product, labor, and equipment-related expenses. While the ingredients of organic herbicides are naturally derived, their high application rates can lead to increased exposure for both the environment and human handlers. Substances like acetic acid and clove oil, common in organic formulations, may cause skin and respiratory irritation if misapplied. These hazards can be exacerbated by less stringent regulations on some organic products compared to synthetics, potentially enabling harmful compounds to remain in soil and water at unsafe concentrations (Dayan et al. 2009; Askew et al. 2024). Another point of concern is the environmental toxicity of certain organic herbicides. Although these products are biodegradable, their broad-spectrum activity can negatively affect non-target organisms, including beneficial soil microbes and aquatic species (Dayan et al. 2009). Thus, the assumption that organic compounds are automatically safer for ecosystems is not always accurate. Furthermore, excessive applications of organic herbicides can create ecological imbalances similar to those associated with synthetic pesticides when not applied following label instructions (Bahlai et al. 2010).

Recent advancements in weed management, such as cryogenic weed control and laser weeding, represent promising alternatives to traditional synthetic and organic herbicides in turfgrass systems (Romero and Askew 2023). Cryogenic treatments work by exposing weeds to

extremely low temperatures, causing cellular damage and eventual plant death, while laser systems selectively target weeds using precision energy beams to destroy tissue (Sakai and Larcher 1987; Cutulle et al. 2013). These technologies are particularly attractive for their ability to reduce chemical usage and minimize environmental impact. However, both methods share significant challenges with organic herbicides, such as high implementation costs and operational complexities. Cryogenic treatments, for example, require specialized equipment and careful calibration to avoid damaging surrounding turfgrass, making them difficult to scale for large areas. Similarly, laser weeding, though highly precise, involves substantial initial investment and technical expertise, limiting its feasibility in many settings. Despite these hurdles, these technologies provide a glimpse into the future of integrated weed management, where innovation can reduce reliance on conventional chemical herbicides while addressing public and environmental safety concerns (Cutulle et al. 2013; Mathiassen et al. 2006; Tran et al. 2023).

Cryogenic weed control using liquid nitrogen (LN)

Cryogenic weed control utilizes extremely low-temperature materials, such as LN to suppress or eliminate undesirable vegetation. Liquid nitrogen is the most common cryogenic liquid for this purpose, operating at temperatures near −196°C. Exposing target plants to such extreme cold, LN induces rapid cellular rupture, protein denaturation, and tissue damage, leading to plant death (Sakai and Larcher 1987; Zohuri 2018). Unlike traditional chemical herbicides, cryogenic techniques are non-residual, reducing environmental risks such as leaching or off-target drift. This environmental advantage makes cryogenic weed control a compelling alternative in turfgrass management systems, where public and ecological safety is paramount. Only a few studies have explored the application of cryogenic liquids for weed control, although all of them were conducted in agricultural systems rather than turfgrass. Cutulle et al. (2013) demonstrated

that LN application at 9.3 kL ha^{-1} controlled large crabgrass [*Digitaria sanguinalis* (L.) Scop.] and pitted morningglory (*Ipomoea lacunosa* L.) in fallow agricultural fields. The study also explored the use of a pressure-ballasted roller to enhance control by crushing flash-frozen weeds; however, its effectiveness varied depending on weed species, nozzle type, and nozzle distance from the target. Fergedal (1993) compared LN to carbon dioxide snow and found LN to be more effective at controlling weeds; he also reported that LN effects on grassy weeds were similar to flaming in terms of control and energy requirements. Both studies highlight the potential of cryogenic weed control but also underscore limitations such as varied output flows and selective applications, as the primary focus was on total vegetation control.

Cryogenic weed control offers several advantages for turfgrass systems. First, LN has a minimal environmental impact, as its mode of action (MOA) is by freezing the plant tissue, leaving no residues that could affect non-target organisms, soil, or water sources. LN is considered a renewable resource since, after application, the liquefied air simply evaporates and returns to the atmosphere, ensuring that no persistent residues remain. Second, LN's physical mode of action induces rapid and irreversible cell rupture through extreme cold. This immediate mechanical disruption is fundamentally different from the biochemical pathways targeted by chemical herbicides. Because LN causes lethal damage upon contact, even at low exposure dosages, it significantly reduces the likelihood that weeds will evolve resistance mechanisms, providing a long-term alternative for weed management. Third, advancements in machine-vision sprayers could enable the precise application of LN, allowing only weeds to be treated while sparing desirable turfgrass. Such precision significantly minimizes collateral damage and reduces the cost of application. Finally, using an individual plant treatment (IPT) or site-specific approach, LN could potentially become a practical and economically feasible solution for those

turf areas where public exposure is a concern, such as playgrounds, schools, or near body waters (Cutulle et al. 2013; Ferdegal 1993; Romero et al. 2025).

However, adapting cryogenic weed control for turfgrass systems poses several significant challenges that must be addressed from both an engineering and a biological perspective. From an engineering standpoint, LN exhibits an expansion ratio of approximately 1:700, meaning that at room temperature, the rapid phase transition from liquid to gas generates a 700 times volumetric increase. This expansion necessitates the use of specialized containment systems capable of managing high internal pressures, as even well-designed insulated vessels experience gradual LN loss over time due to controlled venting or pressure relief. Consequently, further advancements in cryogenic storage and delivery technology are essential to optimize LN preservation and ensure consistent, efficient application (Anonymous 2022).

The turfgrass system presents a unique set of challenges relative to production agriculture. The multi-tiered canopy structure of turfgrass shields emerging weed seedlings, typically the most vulnerable weed stage. In contrast, mature weeds, with their extensive and resilient root systems, may exhibit a reduced sensitivity to cryogenic injury compared to seedlings. This differential susceptibility suggests that a uniform LN treatment may not be equally effective across all weed developmental stages, thereby necessitating the development of variable dosing strategies or the integration of complementary mechanical interventions of LN-delivering devices to enhance overall efficacy.

Cryogenic weed control, like traditional organic herbicides, is inherently non-selective, posing a risk of damage to surrounding turfgrass. This lack of selectivity has hindered its utilization into turfgrass management on a large scale. While it offers a promising alternative to chemical herbicides by reducing environmental residues and addressing herbicide resistance,

significant technological advancements are needed to make it a practical solution for turfgrass systems. LN is not classified as herbicide and, as such, is exempt from the stringent regulatory frameworks that govern synthetic chemical agents. This regulatory latitude and the new developments in artificial intelligence (AI) could incentivize increased investment from both academic researchers and commercial enterprises, as the absence of bureaucratic hurdles associated with chemical approvals may accelerate the development and deployment of innovative techniques and specialized equipment for cryogenic weed control. Its use, however, requires strict adherence to safety guidelines due to the extremely cold temperatures and gas expansion rate involved, which might necessitate specialized safety equipment and operator training.

Laser weed control in turfgrass settings

Laser weeding operates by delivering focused light energy to target weed plants, causing thermal damage that inhibits their growth or leads to death. This is achieved by heating specific plant tissues, such as the apical meristem or stem, to lethal temperatures, resulting in cell rupture and the cessation of physiological functions (Mwitta et al. 2022; Andreasen et al. 2022). The success of laser weed control depends on a variety of factors, including the laser's physical parameters (e.g., wavelength, power, beam diameter, and dose in joules cm^{-2}) and the biological traits of the weeds (such as growth stage, stem thickness, and species) (Heisel et al. 2001; Mathiassen et al. 2006). Thicker-stemmed weeds demand higher energy inputs for effective treatment. Similarly, weeds at early growth stage are more susceptible to laser damage than those at more mature growth stages, highlighting the importance of proper timing in laser applications (Andreasen et al. 2024).

Laser beams are also a non-selective weed control method, like organic treatments. However, recent developments in machine learning have enabled AI systems to identify and differentiate between weeds and desirable species. For instance, neural networks can be trained to recognize weed species with high accuracy (Christensen et al. 2009; Joseph et al. 2024), permitting more selective laser targeting (spot treatment) and reducing collateral damage, an essential concern in turfgrass systems. Robotics play a crucial role in scaling laser weed control for practical use. Autonomous platforms equipped with lasers and AI-driven weed detection capabilities are already commercially available for specialty crops, with prices ranging from $0.5 million to $1 million. Although such systems are not yet widely used in turfgrass management. High-value turf areas like golf putting greens and green surrounds could be prime candidates, as they are particularly sensitive to herbicide injury and often have low-density weeds that escape chemical control. In these scenarios, laser-based technology could offer a precision alternative, where the high costs of AI and robotics might be offset by savings in labor and reduced chemical use (Andreasen et al. 2022; Askew 2023).

Despite its promise, laser weed control faces several challenges that limit broader adoption. In turfgrass, we are dealing with mature weeds, as targeting weeds at the seedling stage is not practical because it is hard to detect with the human eye or machine vision systems. Furthermore, time can be a constraint when using low-power lasers. One solution might be the use of increasingly powerful CO_2 lasers, which operate in the far-infrared (~10.6 μm) and can cut stems or ablate tissues with rapid, high-energy pulses (Heisel et al. 2001). However, more powerful lasers also drive-up equipment costs, reducing economic feasibility for weed management (Tran et al. 2023; Romero et al. 2025).

In contrast, diode lasers operating mainly in the visible to near-infrared spectrum require lower power inputs and often rely on more sustained exposure (e.g., 5–6.1 W over 0.5–1.5 seconds) to achieve weed suppression (Mathiassen et al. 2006). While they may be slower to destroy plant tissue than abrupt, high-energy CO_2 pulses, diode lasers offer advantages in portability and cost efficiency. For instance, the cost for continuous operation of a 10 W diode laser for 7.6 years is estimated at $ 112 in energy consumption. Their comparatively modest cooling requirements might facilitate its integration with autonomous robotic systems equipped with AI-driven weed detection. Nevertheless, as with CO_2 lasers, successful diode-based weed control systems will also depend on robust, well-trained machine-learning models capable of distinguishing weeds, especially those morphologically similar to turf (Mwitta et al. 2022; Coleman et al. 2020; Romero et al. 2025).

Regulatory considerations also come into play. Laser weeding is a relatively new technology, and while there are no specific federal regulations in the U.S. dedicated solely to its use in agriculture, existing laser safety and agricultural regulations still apply. Any equipment modifications or operational protocols may require additional review beneath guidelines set forth by agencies such as the Occupational Safety and Health Administration (OSHA), the Food and Drug Administration (FDA), or the United States Department of Agriculture (USDA), depending on the device's power and classification. These regulatory gaps can further incentivize or delay widespread adoption, as turf managers must ensure compliance with all relevant safety standards and agricultural regulations.

The limited amount of research specifically tailored to turfgrass settings further hinders the adoption of laser weeding in this sector. Most published studies focus on row crops or specialty agriculture, leaving considerable gaps in understanding how best to adapt laser

technologies for dense turf canopies and perennial grass species. Future work should concentrate on optimizing laser parameters (e.g., beam diameter, dose, pattern, and application frequency) and refining AI-driven identification systems to distinguish closely spaced weeds from turf. Laser technology combined with AI and robotics offers a promising direction for sustainable weed management, with the potential to reduce dependence on herbicides and provide precision control. However, issues of cost, energy demands, regulatory frameworks, and selectivity must be addressed before widespread implementation becomes feasible in turfgrass. As research in this area continues, refinements in equipment design, detection algorithms, and operating protocols are likely to improve the practicality and effectiveness of laser weed control, paving the way for its integration into high-value turf management programs.

Machine vision in precision turfgrass weed management

Although machine vision technology was not used in this study, it represents a promising path for future implementation of non-chemical weed control tools like those evaluated here. Because our approaches (liquid nitrogen and laser) depend on highly localized, individual plant targeting, they could benefit significantly from integration with machine vision systems that allow precise weed identification and treatment. Machine vision and machine learning models have the potential to revolutionize weed management by addressing two critical challenges that have historically limited the adoption of organic and non-chemical approaches: poor selectivity and the associated cost (Avent et al. 2024; Petelewicz et al. 2024; Jakhar et al. 2025). Traditional organic weed management methods, such as mechanical tilling or flaming, often lack the precision required to target weeds without damaging turfgrass, leading to inefficiencies and increased labor costs (Koo et al. 2023). However, advancements in machine vision, powered by AI and deep learning, allow for precise differentiation between weeds and desirable plants.

These systems can process high-resolution imagery to identify specific weed species based on shape, color, and other distinguishing features, enabling precise targeted application of control methods such as lasers (Petelewicz et al. 2024; McCurdy et al. 2025). Christensen et al. (2009) demonstrated how AI-based detection algorithms could enhance site-specific weed control by directing energy or treatments only to undesirable plants. This level of precision not only reduces collateral damage but also minimizes energy and resource consumption, making non-chemical methods more cost-effective.

Furthermore, machine vision holds promise for managing herbicide-resistant weeds, a growing concern in both organic and conventional turfgrass systems. By enabling site-specific weed control, machine vision systems can identify scapes from traditional weed management programs and apply alternative treatments, such as laser or cryogenic methods, that are not reliant on chemical pathways. This targeted approach reduces the competitive advantage of resistant weeds and supports integrated weed management strategies aimed at long-term sustainability (Askew et al. 2025).

Turfgrass systems present unique challenges for weed control that differ significantly from those encountered in agricultural crop production. One critical distinction is that turf managers often contend with more mature weeds, which differ from the younger, seedling-stage weeds typically targeted in row crops. In turf, weeds are often well-established by the time they are treated, requiring control methods that can effectively damage or kill mature plants with developed root systems and multiple tillers. Unlike in crops, where seedlings can be selectively targeted at their most vulnerable stage, turf environments demand treatments capable of delivering sufficient tissue damage to either cause weed mortality or suppress growth enough to allow the turfgrass to outcompete the weeds (Askew et al. 2025).

Additionally, the dense and uniform nature of turfgrass systems complicates weed management. Turf weeds often grow in close proximity to desirable grasses, making selectivity and precision critical to avoid damaging the turf itself. The lack of clearly defined rows, as seen in agricultural settings, means that traditional methods relying on spatial separation between crops and weeds are not applicable. Furthermore, the aesthetics of turfgrass, particularly in high-value settings like golf courses, require weed control strategies that not only eliminate unwanted plants but also preserve the visual quality of the turf. These constraints highlight the need for innovative approaches, such as laser or cryogenic methods, that can provide precise, and effective weed control in turfgrass systems as an alternative to herbicides. The primary objectives of this thesis project are -

Research objectives

1. Develop methods to deliver LN and laser energy to turfgrass weeds in known doses.
2. Assess the efficacy of different LN doses to control goosegrass and annual bluegrass in turfgrass.
3. Determine the temporal green color response of various turfgrass and weed species to varied laser intensities and patterns.

References

Anonymous 2022. Hudson Valley Community College. n.d. Liquid Nitrogen Safety Guidelines. Environ. Health & Safety, Troy, NY. Available at: http://www.hvcc.edu/ehs/health/liquid-nitrogen-safety-guidelines.pdf. Accessed February 7, 2025.

Andreasen, C., K. Scholle, and M. Saberi. 2022. Laser weeding with small autonomous vehicles: Friends or foes? Front. Agron. 4:841086. doi:10.3389/fagro.2022.841086.

Andreasen, C., E. Vlassi, and N. Salehan. 2024. Laser weeding: Opportunities and challenges for couch grass (Elymus repens (L.) Gould) control. Sci. Rep. 14:11173. doi:10.1038/s41598-024-61742-8.

Andreasen, C., E. Vlassi, and N. Salehan. 2024. Laser weeding of common weed species. Front. Plant Sci. 15:1375164. doi:10.1038/s41598-024-61742-8.

Askew, S. D., J. D. McCurdy, A. Wilber, J. R. Romero, N. Godara, and P. Le Naour-Vernet. 2025. Evaluation of a machine vision sprayer for weed control in managed turfgrass. Northeastern Weed Sci. Soc. (NEWSS), Annapolis, MD.

Askew, S. D., J. D. McCurdy, A. Wilber, J. R. Romero, N. Godara, and P. Le Naour-Vernet. 2025. Turf and weed response to organic herbicides applied by machine vision sprayer. South. Weed Sci. Soc. (SWSS), Charleston, SC.

Avent, T. H., J. K. Norsworthy, W. L. Patzoldt, L. M. Schwartz-Lazaro, M. M. Houston, T. R. Butts, and A. R. Vazquez. 2024. Comparing herbicide application methods with See & Spray™ technology in soybean. Weed Technol. 38:e74. doi:10.1017/wet.2024.7.

Bahlai, C. A., Y. Xue, C. M. McCreary, A. W. Schaafsma, and R. H. Hallett. 2010. Choosing organic pesticides over synthetic pesticides may not effectively mitigate environmental risk in soybeans. PLOS ONE 5(6):e11250. doi:10.1371/journal.pone.0011250.

Barzman, M., and S. Dachbrodt-Saaydeh. 2011. Comparative analysis of pesticide action plans in five European countries. Pest Manag. Sci. 67:1481–1485. doi:10.1002/ps.2283.

Brosnan, J. T., M. W. Barrett, and P. C. Bhowmik. 2020. Herbicide resistance in turfgrass: A chance to change the future? Weed Technol. 34:431–436. doi:10.1017/wet.2020.28.

Bush, E. A., and L. Rodríguez Salamanca. 2024. Reducing pesticide use in the home lawn and garden. Virginia Coop. Ext., Virginia Tech, Virginia State Univ. Available at: https://www.pubs.ext.vt.edu/450/450-725/SPES-589.pdf.

Christensen, S., H. T. Søgaard, P. Kudsk, M. Nørremark, I. Lund, E. S. Nadimi, and R. Jørgensen. 2009. Site-specific weed control technologies. Weed Res. 49(3):233–241. doi:10.1111/j.1365-3180.2009.00696.x.

Coleman, G., C. Squires, and M. Walsh. 2020. Lasers, machine learning, weed recognition and new innovations in weed management. GRDC Grains Res. Update, Dubbo and Lake Cargelligo. Available at: GRDC website.

Cutulle, M. A., G. R. Armel, J. T. Brosnan, D. A. Kopsell, W. E. Hart, J. J. Vargas, L. A. Gibson, R. E. Messer, A. J. McLemore, and H. A. Duncan. 2013. Evaluation of a cryogenic sprayer using liquid nitrogen and a ballasted roller for weed control. J. Test. Eval. 41(6):1–6. doi:10.1520/JTE20120296.

Dayan, F. E., C. L. Cantrell, and S. O. Duke. 2009. Natural products in crop protection. Bioorg. Med. Chem. 17(12):4022–4034. doi:10.1016/j.bmc.2009.01.046.

Donley, N. 2019. The USA lags behind other agricultural nations in banning harmful pesticides. *Environ Health* **18**, 44 . https://doi.org/10.1186/s12940-019-0488-0

Elmore, M. T., A. J. Patton, T. W. Gannon, and J. T. Brosnan. 2023. Advances in turfgrass weed management. Pages XX–XX in M. Fidanza, ed. Achieving Sustainable Turfgrass Management. Burleigh Dodds Sci. Publ.

Fergedal, S. 1993. Weed control by freezing with liquid nitrogen and carbon dioxide snow—A comparison between flaming and freezing. Rep. No. 165, Dep. Agric. Eng., Swedish Univ. Agric. Sci., Alnarp, Sweden.

Godara, N., R. C. Williamson, D. Koo, and S. D. Askew. 2023. Effect of herbicides on pollinator foraging behavior and flower morphology in white clover (Trifolium repens L.)–infested turfgrass. Weed Technol. 37:221–225. doi:10.1017/wet.2023.33.

G. S. n.d. Pesticide ban puts Europe's golf scene to the test. Golf Sustainable. Available at: https://golfsustainable.com/en/pesticide-ban-puts-europes-golf-scene-to-the-test/. Accessed January 27, 2024.

Heisel, T., J. Schou, S. Christensen, and C. Andreasen. 2001. Cutting weeds with a CO2 laser. Weed Res. 41(1):19–29. doi:10.1046/j.1365-3180.2001.00212.x.

Jakhar, A., S. D. Askew, J. D. McCurdy, A. Wilber, J. R. Romero, N. Godara, and P. Le Naour-Vernet. 2025. Turf and weed response to organic herbicides applied by machine vision sprayer. South. Weed Sci. Soc. (SWSS), Charleston, SC.

Joseph, M. M., K. A. Gawron, C. Zhao, G. E. MacDonald, A. W. Schumann, N. S. Boyd, and P. Petelewicz. 2024. Evaluation of segmentation and semi-supervised learning for spotted spurge recognition in bermudagrass turf. Int. Turfgrass Soc. Res. J. doi:10.1002/its2.152.

Koo, D., C. G. Goncalves, and S. D. Askew. 2023. Organic chemicals for weed control in dormant turf [Abstract]. ASA, CSSA, SSSA Int. Annu. Meet., St. Louis, MO. Available at: https://scisoc.confex.com/scisoc/2023am/meetingapp.cgi/Paper/149576.

Mathiassen, S. K., T. Bak, S. Christensen, and P. Kudsk. 2006. The effect of laser treatment as a weed control method. Biosyst. Eng. 95(4):497–505. doi:10.1016/j.biosystemseng.2006.08.010.

McCarty, L. B., T. R. Murphy, and A. J. Turgeon. 1994. Control of turfgrass weeds. Pages 209–248 in A. J. Turgeon, ed. Turf Weeds and Their Control. Madison, WI: ASA and CSSA.

McCurdy, J. D., R. G. Bowling, A. J. Patton, A. R. Kowalewski, C. M. Mattox, J. T. Brosnan, D. E. Ervin, S. D. Askew, C. G. Goncalves, M. T. Elmore, J. S. McElroy, B. C. McNally, B. D. Pritchard, J. E. Kaminski, and M. V. Bagavathiannan. 2023. Developing and implementing a sustainable, integrated weed management program for herbicide-resistant Poa annua in turfgrass. Crop Forage Turfgrass Manag. 9(1):e20225. doi:10.1002/cft2.20225.

McCurdy, J. D., A. Wilber, S. D. Askew, J. R. Romero, N. Godara, and P. Le Naour-Vernet. 2025. Targeting dallisgrass and other weeds in warm-season turfgrass systems using the Ecorobotix ARA. South. Weed Sci. Soc. (SWSS), Charleston, SC.

McElroy, J. S., and P. C. Bhowmik. 2013. Turfgrass weed management. Agron. Monogr. 56:777–808. doi:10.2134/agronmonogr56.c22.

McElroy, J. S., and D. Martins. 2013. Use of herbicides on turfgrass. Planta Daninha 31:455–467. doi:10.1590/S0100-83582013000200024.

Mwitta, C., G. C. Rains, and E. Prostko. 2022. Evaluation of diode laser treatments to manage weeds in row crops. Agronomy 12(11):2681. doi:10.3390/agronomy12112681.

Petelewicz, P., Q. Zhou, M. Schiavon, G. E. MacDonald, A. W. Schumann, and N. S. Boyd. 2024. Simulation-based nozzle density optimization for maximized efficacy of a machine

vision–based weed control system for applications in turfgrass settings. Weed Technol. 38:e25. doi:10.1017/wet.2024.7.

Romero, J. R., and S. D. Askew. 2023. Individual plant treatment with cryogenic liquids [Abstract]. ASA, CSSA, SSSA Int. Annu. Meet., St. Louis, MO. Available at: https://scisoc.confex.com/scisoc/2023am/meetingapp.cgi/Paper/150697.

Romero, J. R., N. Godara, and S. D. Askew. 2025. An individual plant treatment system for evaluating goosegrass response to liquid nitrogen. Northeastern Weed Sci. Soc. (NEWSS), Annapolis, MD.

Romero, J. R., N. Godara, and S. D. Askew. 2025. Is laser energy practical for weed management in turfgrass? South. Weed Sci. Soc. (SWSS), Charleston, SC.

Sakai, A., and W. Larcher. 1987. Frost survival of plants: Response and adaptation to freezing stress. Pages 303–326 in W. D. Billings, F. Golley, O. L. Lange, J. S. Olson, and H. Remmert, eds. Springer, Berlin.

Tran, D., J. J. Schouteten, M. Degieter, J. Krupanek, W. Jarosz, A. Areta, L. Emmi, H. De Steur, and X. Gellynck. 2023. European stakeholders' perspectives on implementation potential of precision weed control: The case of autonomous vehicles with laser treatment. Precis. Agric. doi:10.1007/s11119-023-10037-5.

Zohuri, B. 2018. Cryogenic technologies. Pages 1–51 in Physics of Cryogenics. doi:10.1016/B978-0-12-814519-7.00001-X.

Short title: Liquid nitrogen weed control

A Targeted Application System for Evaluating Goosegrass and Annual Bluegrass Response to Liquid Nitrogen

Juan R. Romero[1], Navdeep Godara[2], and Shawn D. Askew[3]

[1]Graduate Assistant (ORCID 0009-0002-7456-0054), School of Plant and Environmental Sciences, Virginia Polytechnic Institute and State University; [2]Graduate Assistant (ORCID 0000-0002-1452-5225), School of Plant and Environmental Sciences, Virginia Polytechnic Institute and State University; and [3]Professor (ORCID 0000-0002-9515-9502), School of Plant and Environmental Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA

Author for correspondence: Shawn D Askew, Professor, School of Plant and Environmental Sciences, Virginia Polytechnic Institute and State University, 675 Old Glade Road, Blacksburg, VA 24061

E-mail: saskew@vt.edu

Abstract

Herbicide-resistant weed populations such as goosegrass (*Eleusine indica* L) and annual bluegrass (*Poa annua* L) continue to challenge effective management in turfgrass systems. Liquid nitrogen (LN) offers a nonchemical alternative capable of rapidly destroying plant tissue through cryogenic damage, though its lack of selectivity has historically limited turfgrass applications. This study developed and evaluated a targeted LN delivery system capable of applying controlled doses to individual weeds. A total of four field trials were conducted across two sites in Blacksburg, VA to evaluate dose-response relationships for goosegrass and annual bluegrass. The custom device dispensed approximately LN at 3.2 $mL \cdot s^{-1}$, and seven LN doses (0–5.1 mL) were tested in this study. Logistic regression revealed that 90% control of goosegrass and annual bluegrass was achieved with doses ≥2.2 mL. Annual bluegrass response was consistent across trials, while goosegrass exhibited trial-dependent recovery at lower doses. LN caused rapid and substantial reduction in green cover for both species, with limited regrowth. Results demonstrate LN's potential as an organic weed control method in turfgrass, especially when paired with precision targeting. Future research should evaluate turfgrass recovery under repeated applications and explore integration with autonomous robotic systems.

Nomenclature: Goosegrass, *Eleusine indica* L. Annual bluegrass, *Poa annua* L.

Key words: Cryogenic liquid, dose response, organic weed control, turfgrass.

Introduction

Weed control in managed turfgrass systems has leaned heavily on synthetic herbicides, fostering herbicide-resistant populations of problematic weeds like goosegrass (*Eleusine indica* L. Gaertn.) and annual bluegrass (*Poa annua* L.) (Allen et al. 2022; Heap 2014; Peppers and Askew 2025; Powles and Yu 2010; Rutland et al. 2023). The International Survey of Herbicide-resistant Weed Database reports 534 unique cases of resistant biotypes globally, with 8 weed species in turfgrass system evolved resistance (Heap 2025). Annual bluegrass, prevalent in high-value turf like golf courses, was documented as resistant to six different herbicide modes of action (MOA), followed closely by goosegrass resistance cases in similar settings (Brewer and Askew 2021; Brosnan et al. 2020; Heap 2025; McCurdy et al. 2023). Herbicide development has slowed, producing only two new MOA in the past 30 years compared to one every two years from the 1950s to 1980s, which, amid regulatory bans like Portland, Maine's 2018 synthetic pesticide prohibition, worsened weed control challenges (Dayan 2019; Duke et al. 2024; Wilcox 2021).

Turfgrass management prioritizes aesthetics (e.g., uniformity, color, and functionality) distinguishing it from agronomic systems where yield-preserving is the goal and aesthetic injury by herbicides is more acceptable (Beard 1972; Burke et al. 2005; Turgeon 2011). This demand for selectivity has constrained nonselective organic treatments, including cryogenic methods, which damage desirable grasses alongside weeds (Patton and Weisenberger 2012). Organic herbicides, endorsed by the Organic Materials Review Institute (OMRI), have risen in popularity as consumer and regulatory pressures favor ecofriendly options (Askew et al. 2025b; Fogliatto et al. 2023; Neal 2024). Yet, Reiter and Windbiel-Rojas (2020) found that 10 OMRI-certified products, such as acetic acid, provided only transient burndown in turfgrass, with rapid weed regrowth and turf injury. Askew et al. (2025a) tested 14 nonsynthetic herbicides for annual

bluegrass, reporting inconsistent control and aesthetic damage, highlighting the selectivity barrier that has historically sidelined nonselective organic options like liquid nitrogen (LN).

LN offers a potential alternative to chemical herbicides, flash-freezing plant tissues at -195.8°C to form ice crystals that rupture cell membranes (Cutulle et al. 2013; Romero et al. 2025). Fergedal (1993) showed LN's efficacy rivaled flaming for grass control, while Cutulle et al. (2013) controlled pitted morningglory in row crops spraying LN at 9,360 L/ha followed by a mechanical roller. In turf, LN's nonselective nature, logistical challenges (storage, handling), and lack of targeted delivery have limited its use (Fergedal 1993; Loddo et al. 2021). Unlike herbicides, LN leaves no chemical residues, aligning with organic preferences. Its use, however, risks aesthetic degradation, critical in golf courses and athletic fields, unless applied precisely.

Recent precision technologies may offer solutions to improve the selectivity of LN by targeted placement only to weeds while minimizing collateral damage to turfgrass. Machine vision has revolutionized selective weed control in crops, targeting individual plants with herbicides or lasers (Hahn et al. 2020; Riccaboni et al. 2021). Furthermore, technological advancements have been made in turfgrass systems. Kitchin et al. (2024) demonstrated that a DeepLabV3 + model can be trained to identify and quantify dollar spots in turfgrass. Their findings also suggested the potential to apply deep learning algorithms for other turfgrass diseases. On the commercial side, tools like GreenKeeper (TurfGrade, LLC) use artificial intelligence (AI) to analyze a complex set of data that includes historical information, weather and geospatial data to predict pest outbreaks and improve turf management and resource allocation (Kreuser 2023).

LN can be generated on-site via air separation units, producing cryogenic air at ~$50–100 ha^{-1} for small-scale setups—potentially competitive with herbicide like glyphosate ($30–70 ha^{-1})

in golf courses or sports facilities (Rutherford & Titan 2022; Romero et al. 2025). Bulk LN storage with automated transfer systems (e.g., insulated hoses, robotic nozzles) could minimize volatility losses and labor, though scaling to turfgrass settings remains unproven (Romero et al. 2025). Golf courses might integrate such systems, but costs and safety remain essential before widespread adoption. Safety considerations are paramount due to the inherent risks associated with cryogenic technology. LN expands rapidly upon evaporation, converting from liquid to gas at a volumetric expansion ratio of approximately 1:694, meaning 1 liter of liquid nitrogen produces nearly 700 liters of nitrogen gas (USDA 2025). Improper storage or handling can cause significant pressure build-up; sealed or inadequately vented containers can generate extreme pressures, potentially thousands of psi, posing serious explosion hazards (BCC 2018). Direct skin exposure to LN can result in severe cryogenic burns or frostbite within seconds of contact.

LN utilization has established safety protocols across industries but lacks detailed guidance for precise agricultural applications, particularly weed control (Cutulle et al. 2013). Unlike industrial or medical uses, where LN volume precision in mL is rarely critical, a precise application in turfgrass demands controlled delivery of minimal doses to reduce waste and costs, yet no standardized method exists. Cutulle et al. (2013) faced significant challenges quantifying LN for greenhouse crabgrass control, noting rapid vaporization and difficulty controlling application dose. Factors potentially affecting LN measurements included ambient temperature, device temperature, physical movement, ice buildup, and pressure fluctuations. Applications at field scale relied on indirect measures (tank volume and dispensing time) with output adjusted by tractor speed, not dependent on nozzle flow. This contrasts with conventional sprayers, which offer precise dose adjustments, underscoring LN's logistical hurdles in weed management. These gaps highlight the need for a targeted LN delivery system in turfgrass, where selectivity and

aesthetics are paramount. This study developed an LN delivery system to mimic precision applicators, targeting individual weeds like goosegrass and annual bluegrass in turfgrass. We engineered a device to apply controlled LN doses, adjusted for volatility, and evaluated a dose range on the above-mentioned problematic weed species. Our objective was to assess LN's weed control efficacy in annual bluegrass and goosegrass.

Materials and Methods

Custom LN Dispenser Design and Output Rate

To overcome challenges in delivering precise LN doses for weed control, a custom dispenser was constructed (Figure 1). The device includes a timer relay (DROK 12-volt; Guangzhou, China) programmable in 0.1-second increments, which controls a cryogenic solenoid valve (Alcon 68 series; Rotork, Bath, United Kingdom) at the dispenser's base to regulate LN flow. The system is enclosed in a 23-cm wide × 30-cm high insulated box containing a double-walled cup to maintain LN at low temperatures and minimize volatilization. Initial preliminary tests confirmed the custom dispenser could contain and dispense LN, prompting calibration of dispensing rates in $mL \cdot s^{-1}$. Direct measurement of LN in the device was challenging due to boiling and evaporation, exacerbated by a 0.6-cm metal pipe exiting the reservoir and connecting the solenoid, which broke the air insulation and increased fluid agitation. To address this, preliminary studies were conducted in the laboratory at constant 24 C temperature. First, 500 mL of LN (specific density 0.808 $g \cdot mL^{-1}$, equivalent to 404 g) was measured in a separate insulated glass using a scale (Sutekus T500E) where the fluid remained stable. Transferring LN to the dispenser resulted in consistent volume loss, quantified by weighing the empty device (baseline) and again after adding 500 mL of LN. Across twenty

transfers, an average loss of 13.87 mL per transfer with a standard error of 0.35 mL was recorded.

Volatilization losses during storage were assessed by monitoring weight changes every 60 seconds with the solenoid closed (no dispensing). Repeated trials revealed a consistent volatilization rate of 0.31 $mL \cdot s^{-1}$. An earlier prototype used two 35-psi pressure-release valves to manage safety risks from volumetric expansion, but excessive noise led to their replacement with a lid featuring a 1.2-cm-diameter vent hole. While this reduced noise and improved safety, it increased volatilization, as reflected in the measured rate. To determine the dispensing rate, the timer relay was set to remain open after filling the device with 500 mL of LN. The time from opening until the device emptied was recorded across multiple replications, yielding an average rate of 3.52 $mL \cdot s^{-1}$. Accounting for transfer loss (13.87 mL) and volatilization (0.31 $mL \cdot s^{-1}$ over dispensing time), the effective dispensing rate was determined to be 3.2 $mL \cdot s^{-1}$.

Field Studies

Four field studies were conducted at the Glade Road Research Facility, GRRF (37°14'03"N, 80°26'10"W) and the Turfgrass Research Center, TRC (37°12'54"N, 80°24'46"W) in Blacksburg, VA, from September to December 2024 to assess LN doses to control goosegrass and annual bluegrass (Table 1). Goosegrass experiments were conducted on fallow sites at both locations, targeting mature, actively growing plants with 4 to 6 tillers at the timing of trial initiation. To isolate target plants and minimize data collection errors, weeds were selected from a larger population based on uniform size. Surrounding vegetation within approximately 1 dm^2 was hand-weeded to reduce interference. A placement guide, consisting of a wooden platform with a 3.5-cm diameter hole, was used to center each selected weed within the hole as the platform was positioned. A liquid nitrogen (LN) applicator was then placed on the platform

(Figure 1), aligning the nozzle directly over the weed for precise application. Seven LN doses (0, 0.6, 1.0, 2.2, 2.9, 4.2, and 5.1 mL) were applied to goosegrass, with 10 replicates per dose. The experiment was arranged as a single-factor completely randomized design.

Annual bluegrass studies spanned two sites: a dormant Zeon zoysiagrass fairway at GRRF and a dormant 'Patriot' bermudagrass fairway at TRC, both heavily infested with annual bluegrass but with minimal turf cover (Table 1). Selected plants were mature, averaging 3 cm in diameter (~7.06 cm^2), and treated with the same seven treatments used on goosegrass, each with six replicates in an RCBD. Irrigation, herbicides, or fertilizers were not applied during the study duration.

Digital images were captured using a Canon EOS 5D Mark IV camera (Tokyo, Japan) within a custom lightbox (1.22 m tall x 0.62 m wide) illuminated with two visible lights (Husky 1000 lumens LED) at 0, 3, 7, 14, 21, and 28 days after treatment (DAT) to assess green cover. Images were analyzed with Turf Analyzer software (Green Research Services, LLC; Fayetteville, AR), comparing green cover reduction at each interval to pre-treatment levels for each species.

Statistical Analysis

LN Dose was considered as a fixed effect, while replication and experimental run were considered as a random effect in the model statement. The green cover reduction response variable for goosegrass and annual bluegrass was subjected to ANOVA using PROC GLM in SAS v 9.3 (SAS Institute, Cary, NC). If the LN dose main effect or LN dose x experimental run interaction for green cover reduction was significant, means of LN doses were fit to a three-parameter logistic nonlinear regression model,

$$Y = C + \frac{D - C}{1 + eb(X - E)}$$

where Y is the percentage green cover reduction (%) at a given LN dose (X, mL/plant), C is the lower asymptote, D is the upper asymptote, b is the slope, and E is the effective dose for 50% reduction (I50). Coefficients of determination (R^2) were calculated for nonlinear regressions as in other studies (Bailey et al. 2003) by subtracting the ratio of residual sums of squares (RSS) to corrected total sums of squares (CTSS) from 1 (i.e., R2 5 1 2 RSS/CTSS).

Results and Discussion

Dose-Response of Goosegrass and Annual Bluegrass to Liquid Nitrogen

The application of LN significantly reduced green cover of goosegrass at 3 and 28 days after treatment (DAT) and at 3 and 28 DAT for annual bluegrass across the Glade and TRC sites. For goosegrass, the LN treatment effect was significant at 3 DAT (P = 0.0096, F = 8.6, df = 6), and not dependent on trial (P = 0.101, F = 1.82, df = 6). However, at 28 DAT, significant interactions between trial and treatment (P = 0.0208) suggested distinct responses across trials, necessitating separate or trial-specific interpretations. The trial dependency primarily influenced goosegrass response at lower LN doses where goosegrass was controlled more rapidly as dose increased at TRC 28 DAT. Since responses at 3 DAT were consistent across trials, it can be speculated that differences at 28 DAT are due to changes in the rate of weed recovery from lower doses. At TRC, growing conditions were less optimal for goosegrass growth and recovery following treatment, thus increasing effective control at lower doses 28 DAT. Notably, the second goosegrass experiment at TRC coincided with dry conditions in Blacksburg, with no rainfall (data not shown) and early-day temperatures of 45–57°F.

Regardless, the upper asymptote of cover reduction 28 DAT was similar for both locations, occurring at approximately 2 mL of LN (Figure 2). The calculated 90% inhibition levels (I_{90}) at 28 DAT were 2.3 at GRRF and 2.9 mL at TRC (see Figure 2). "Commercially acceptable" goosegrass control is often reported to be at least 80% (Brewer et al. 2022a, 2022b), yet, herbicide programs for annual grass control in turf often fail to reach commercially acceptable levels (Brewer and Askew 2021; Kerr et al. 2019; Willis and Askew 2009). In the current study, 2 to 3 mL of LN was sufficient to achieve this level of control (Figure 2).

For annual bluegrass, LN application also exhibited dose-dependence at both 3 DAT ($P = 0.0005$, $F = 24.85$, $df = 6$) and 28 DAT ($P = 0.0031$, $F = 13.28$, $df = 6$), and neither response was dependent on trial ($P > 0.05$). Trends in green cover reduction fitted to a logistic equation were similar at both 3 and 28 DAT indicating rapid action of LN on annual bluegrass cover reduction (Figure 3). Calculated 50% green cover reduction (I_{50}) was 1.2 to 1.3 mL LN at 3 and 28 DAT, respectively, showing slight recovery of annual bluegrass plants by 28 DAT following low doses (Figure 3). Annual bluegrass cover 28 DAT was reduced 90% by LN at 2.2 mL (Figure 2). This pattern suggests that annual bluegrass at this stage (3-cm diameter) requires similar doses for 90% control compared to goosegrass, although goosegrass was less consistent, requiring a higher dose at one of two locations (Figure 2).

The efficacy of LN for controlling both goosegrass and annual bluegrass aligns with its cryogenic effects, where rapid freezing disrupts cellular membranes, metabolism, and meristematic regions, affecting regrowth (Larson 1993; Cutulle et al. 2013). The dose-dependent response observed indicates that higher LN volumes cause greater tissue damage, leading to near-total mortality (≥ 90%) at doses ≥ 2.2 mL for both species (Figure 2). Unlike synthetic herbicides, LN does not rely on enzymatic inhibition or systemic translocation but induces

mechanical cell rupture and desiccation, likely making it effective against herbicide-resistant weed populations (Cutulle and Maja 2021; Askew et al. 2025). The differentiated responses across sites for goosegrass suggest that soil moisture, ambient temperature, and plant physiology influence LN performance, warranting further investigation into environmental and biological factors. Likewise, weeds in these studies were mature and, thus, required twice as much LN compared to studies where an estimated LN rate was applied to seedling weeds (Cutulle et al. 2013). Thus, future studies should assess how weed growth stage influences responses to LN doses.

Practical Implications

Liquid nitrogen induces rapid symptom development in annual bluegrass and goosegrass, resembling the effects of herbicides that disrupt photosynthetic electron transport. This process quickly compromises cell membranes, leading to swift cellular destruction, similar to ice-nucleation-mediated membrane disruption caused by LN. Annual bluegrass and goosegrass control by moderate doses of LN were comparable to market-leading synthetic herbicides like foramsulfuron (Willis and Askew 2009), topramezone (Cox et al. 2017, Kerr et al. 2019) mesotrione (Elmore et al. 2013; Goddard et al. 2021; Goncalves et al. 2021), and fenoxaprop (Brewer and Askew 2021), which achieved 80 to 95% weed control under optimal conditions. However, LN offers a residue-free alternative, making it ideal for organic weed management and sensitive areas in turfgrass settings where chemical residues are a concern. From a sustainability and safety perspective, LN's primary limitations are its energy-intensive production via high-pressure distillation (Mehrpooya et al. 2015), high-pressure build-up, and the risk of burns during improper handling. Advances in stirling cooler technology and localized LN generation could reduce costs, enhancing its feasibility for commercial turfgrass applications (Minale et al. 2024).

Integrating LN with precision application systems, such as robotic sprayers, could minimize LN waste, optimize field efficiency, and improve cost-effectiveness for controlling troublesome weeds in golf courses and sports fields. Future research should investigate long-term turfgrass responses to repeated LN applications in perennial systems to assess potential impacts on turfgrass health and soil ecology.

Acknowledgments

The authors would like to thank Matthew Cutulle for technical discussions and insight.

Funding

This research was partially funded by The Virginia Agricultural Council in association with the Virginia Turfgrass Foundation (Project Number 858).

Competing Interests

The authors declare none.

References

Allen JH, Ervin DE, Frisvold GB, Brosnan JT, McCurdy JD, Bowling RG, Patton AJ, Elmore MT, Gannon TW, McCarty LB, McCullough PE, Kaminski JE, Askew SD, Kowalewski AR, Unruh JB, McElroy JS, Bagavathiannan MV (2022) Herbicide-resistance in turf systems: insights and options for managing complexity. Sustainability.; 14:13399

Askew SD, Gonçalves CG, Romero JR, De Castro EB, McCurdy JD, McKeithen C, Unruh JB, Tang K, Kaminski JE (2025a) Nonsynthetic herbicides for turfgrass: assessing frequency of consumer information and regional performance for annual bluegrass (*Poa annua* L.) control. International Turfgrass Society Research Journal, 1-10

Askew SD, Koo D, Goncalves CG, Hale S (2025b) Nonsynthetic herbicides for turfgrass: optimizing performance of acid- and oil-based chemicals via sequential treatment to dormant turfgrass. Int Turf Soc Res J (Accepted)

Bailey WA, Askew SD, Dorai-Raj S, and Wilcut JW (2003) Velvetleaf (*Abutilon Theophrasti*) interference and seed production dynamics in cotton. Weed Sci 51: 94–101 https://doi.org/10.1614/0043-1745(2003)051[0094:VATIAS]2.0.CO;2.

Beard JB (1972) Turfgrass: Science and Culture. Englewood Cliffs, NJ: Prentice Hall.

Brosnan JT, Elmore MT, Bagavathiannan MV (2020) Herbicide-resistant weeds in turfgrass: current status and emerging threats. Weed Technology. 2020;34(3):424-430. doi:10.1017/wet.2020.29

Burke IC, Troxler SC, Askew SD, Wilcut JW, Smith WD (2005) Weed management systems in glyphosate-resistant cotton. Weed Technol 19:422–429

Brewer JR, Askew WLB, Askew SD (2022a) Differences in selectivity between bermudagrass

and goosegrass (Eleusine indica) to low-rate topramezone and metribuzin combinations. Weed Sci. doi:10.1017/wsc.2021.52

Brewer JR, Craft* JM, Askew SD (2022b) Influence of post-treatment irrigation timings and herbicide placement on bermudagrass and goosegrass (Eleusine indica) response to low-dose topramezone and metribuzin programs. Weed Sci.. doi:10.1017/wsc.2021.80

Brewer JR, Askew SD (2021) Investigating low-dose herbicide programs for goosegrass (Eleusine indica) and smooth crabgrass (Digitaria ischaemum) control on creeping bentgrass greens. Weed Technol., 35(4), 604-610. doi:10.1017/wet.2021.55

BCC, British Cryogenics Council (2018). Cryogenics safety manual: a guide to good practice. 5th ed. Accessed: March 29, 2025. Available at: https://bcryo.org.uk/system/files/BCC%20Safety%20Manual%205th%20edition_0.pdf.

Cox MC, Rana SS, Brewer JR, Askew SD (2017) Goosegrass and Bermudagrass Response to Rates and Tank Mixtures of Topramezone and Triclopyr. Crop Science, 57(S1), S-310-S-321. https://doi.org/10.2135/cropsci2016.05.0439

Cutulle MA, Armel GR, Brosnan JT, Kopsell DA, Hart WE, Vargas JJ, Gibson LA, Messer RE, McLemore AJ, Duncan HA (2013) Evaluation of a Cryogenic Sprayer Using Liquid Nitrogen and a Ballasted Roller for Weed Control, Journal of Testing and Evaluation, Vol. 41, No. 6, pp. 1–6, doi:10.1520/JTE20120296. ISSN 00903973

Cutulle MA, Maja JM (2021) Determining the utility of an unmanned ground vehicle for weed control in specialty crop systems. Italian Journal of Agronomy, 16(4), 1865. https://doi.org/10.4081/ija.2021.1865

Dayan FE (2019). Current Status and Future Prospects in Herbicide Discovery. Plants, 8(9), 341. https://doi.org/10.3390/plants8090341

Duke SO (2012). Why have no new herbicide modes of action appeared in recent years? Pest Management Science, 68(4), 505-512. https://doi.org/10.1002/ps.2333

Duke SO, Twitty A, Baker C, Sands D, Boddy L, Travaini ML, Sosa G, Polidore ALA, Jhala AJ, Kloeber JM, Jacq X, Lieber L, Varela MC, Lazzaro M, Alessio AP, Ladner CC, Fourches D, BlochI, Gal M, GresselJ, Putta K, Phillip Y, Shub I, Ben-Chanoch E, Dayan FE (2024) New Approaches to Herbicide and Bioherbicide Discovery. Weed Sci. 72: 444–464. doi: 10.1017/wsc.2024.

Elmore MT, Brosnan JT, Breeden GK, Patton AJ (2013) Mesotrione, topramezone, and amicarbazone combinations for postemergence annual bluegrass (Poa annua) control. Weed Technol 27:596–603 10.1614/WT-D-12-00153.1

Fergedal S (1993) Weed Control by Freezing With Liquid Nitrogen and Carbon Dioxide Snow—A Comparison between Flaming and Freezing, Report No. 165, Department of Agricultural Engineering, Swedish University of Agricultural Science, Alnarp, Sweden.

Fogliatto S, Andres A, Concenço G, Vidotto F, Knezevic S (2023) Editorial: Weed management in organic agriculture. Frontiers in Agronomy, 4, 1116519. https://doi.org/10.3389/fagro.2022.1116519

Hahn D, Sallenave R, Pornaro C, Leinauer B (2020) Managing cool-season turfgrass without herbicides: Optimizing maintenance practices to control weeds. Crop Science, 60(5), 2204-2220. https://doi.org/10.1002/csc2.20175

Heap I (2014). Global perspective of herbicide-resistant weeds. Pest Management Science, 70(9), 1306-1315. https://doi.org/10.1002/ps.3696

Heap I The International Herbicide-resistant Weed Database. Online, Friday, February 14, 2025, Available. https://www.weedscience.org/Pages/Filter.aspx 1993- 2025 WeedScience.org All rights reserved.

Goddard MJR, Goncalves CG, Askew SD (2021) Simulated controlled-release mesotrione for turfgrass tolerance and weed control. Weed Technol., 35(4), 582-588 doi:10.1017/wet.2021.19

Goncalves CG, Ricker DB, Askew SD (2021) Perennial ryegrass phytotoxicity increases with mesotrione rate and growth-promoting environmental conditions. Crop Sci., 61(5), 3155-3163. doi:10.1002/csc2.20407

Kerr RA, McCarty LB, Cutulle M, Bridges W, Saski C (2019) Goosegrass control and turfgrass injury following metribuzin and topramezone application with immediate irrigation. Hortic. Sci. 54:1621-1624

Kitchin A, Sneed E, McCall D (2025) Leveraging deep learning for dollar spot detection and quantification in turfgrass. Crop Sci Madison (WI): Crop Science Society of America; 65(1):e21329. Available from: https://doi.org/10.1002/csc2.21329

Kreuser B (2023) Evolution of data-driven turf management. GreenKeeper; Accessed: March 29, 2025. Available from: https://www.greenkeeperapp.com/evolution-of-data-driven-turf-management/

Larson S, (1993) Environmental Impact Assessment of Thermal Weed Control Methods on Hard Surfaces—A Comparison between Flaming With LPG and Freezing With Liquid Nitrogen and Carbon Dioxide Snow," Report No. 168, Department of Agricultural Engineering, Swedish University of Agriculture, Alnarp, Sweden.

Loddo D, McElroy JS, Giannini V (2021) Problems and perspectives in weed management. Italian Journal of Agronomy, 16(4), 1854. https://doi.org/10.4081/ija.2021.1854

McCurdy JD, Bowling RG, Patton AJ, Kowalewski AR, Mattox, CM, Brosnan JT, Ervin DE, Askew SD, Goncalves CG, Elmore MT, McElroy JS, McNally BC, Pritchard BD, Kaminski JE, Bagavathiannan, MV (2023). Developing and implementing a sustainable, integrated weed management program for herbicide-resistant Poa annua in turfgrass. Crop, Forage & Turfgrass Management, 9(1), e20225. https://doi.org/10.1002/cft2.20225

Mehrpooya M, Moftakhari Sharifzadeh MM, Rosen MA (2015) Optimum design and exergy analysis of a novel cryogenic air separation process with LNG (liquefied natural gas) cold energy utilization. Energy, 90, 2047-2069. https://doi.org/10.1016/j.energy.2015.07.101

Minale TA, Lanzetta F, Bégot S, Getie M Z (2024) Review on the technological advancement of Stirling cycle heat pumps. Energy Reports, 12, 3504-3518. https://doi.org/10.1016/j.egyr.2024.09.028

Neal JC (2024) Biological Control of Weeds in turfgrass: Opportunities and misconceptions. Pest Management Science, 80(1), 40-48. https://doi.org/10.1002/ps.7436

Patton A, Weisenberger D (2012). Efficacy of Current Organic Postemergent Weed Control Options in Turfgrass Systems 2011 Annu. Rep. - Purdue Univ. Turfgrass Sci. Progr. p. 26-30.

Peppers JM, Askew SD (2025) Evaluation of spring-applied endothall for annual bluegrass control in warm-season turf. Weed Technol 39:e29.

Powles S B, Yu Q (2010). Evolution in action: Plants resistant to herbicides. Annual Review of Plant Biology, 61, 317–347. https://doi.org/10.1146/annurev-arplant-042809-112119

Reiter M, Windbiel-Rojas K (2020) Organic herbicides and glyphosate for weed control: Results of coordinated experiments in urban landscapes. CAPCA Adviser Magazine, 23(1), 24-25. California Association of Pest Control Advisers. https://issuu.com/capcaadviser/docs/202002_capca_adv_feb2020_web/24

Riccaboni A, Neri E, Trovarelli F, Pulselli RM (2021) Sustainability-oriented research and innovation in 'farm to fork' value chains. Current Opinion in Food Science, 42, 102-112. https://doi.org/10.1016/j.cofs.2021.04.006

Romero JR, Godara N, Askew SD (2025) An Individual Plant Treatment System for Evaluating Goosegrass Response to Liquid Nitrogen. Northeastern Weed Science Society (NEWSS). Annapolis, Maryland.

Rutherford & Titan (2022) The price of liquid nitrogen in the United States. Rutherford & Titan. Available at: https://www.rutherfordtitan.com/liquid-nitrogen-generators/liquid-nitrogen-price-usa/. Accessed April 3, 2025.

Rutland CA, Bowling RG, Russell EC, Hall ND, Patel J, Askew SD, McElroy JS (2023) Survey of target site resistance alleles conferring resistance in Poa annua. Crop Sci., 63(5), 3110-3121. doi:10.1002/csc2.21066

Turgeon AJ (2011) Turfgrass Management. 9th ed. Upper Saddle River, NJ: Prentice Hall.

USDA (United States Department of Agriculture) (2025). Liquid nitrogen safety. Available at: https://www.ars.usda.gov/northeast-area/docs/safety-health-and-environmental-training/liquid-nitrogen-safety/. Accessed: March 29, 2025.

Wilcox M (2021, November 16). The pesticide ban movement gains momentum. Environmental Health News. Retrieved from https://www.ehn.org/banned-pesticides-2655520575.html

Willis JB, Askew SD (2009) Foramsulfuron applied before and during establishment of seeded bermudagrass. Int. Turfgrass Soc. Res. J. 11:1229-1236.

Table 1. Research experiments were conducted in Blacksburg, VA and to evaluate the effects of liquid nitrogen in two weed species.

Trial[a]	Site type	Weed/Turf	Application	Coordinates	Soil type[b]	Soil pH	Soil OM
						%	%
GRRF2	Roadside	Goosegrass	Oct 1, 2024	37°14'01-80°26'08	S2	6.4	3.4
TRC3	Roadside	Goosegrass	Oct 10, 2024	37.215059-80.412774	S2	6.2	3.1
GRRF4	Zoysiagrass fairway	Annual bluegrass	Dec 05, 2024	37°14'01-80°26'13	S1	6.5	3.5
TRC5	Bermudagrass fairway	Annual bluegrass	Dec 05, 2024	37°12'42-80°24'46	S2	6.5	3.5

[a]Trial descriptions:

[b]Soil taxonomy: S1- Fine-loamy, mixed, active, mesic Ultic Hapludalfs; S2- Fine, mixed, active, mesic Typic Hapludults.

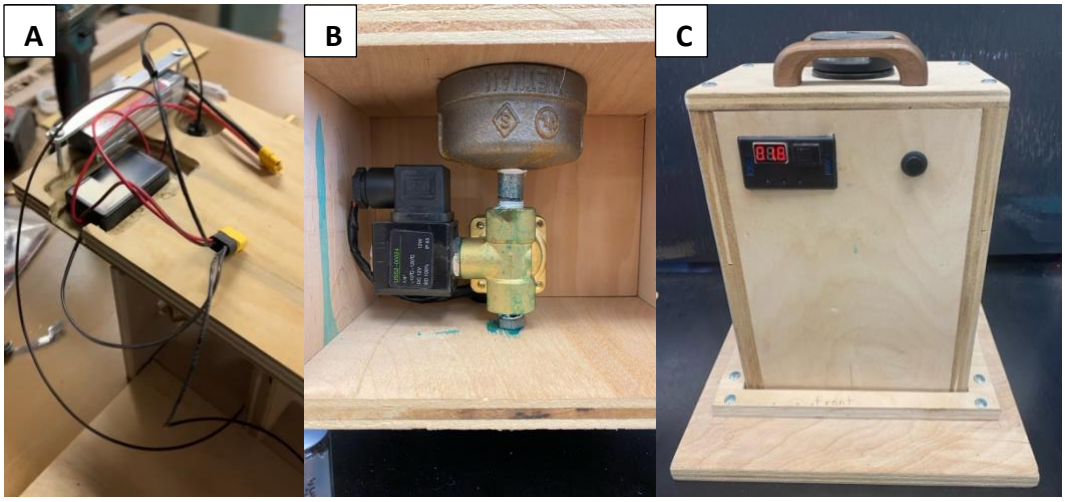

Figure 1.: Custom-built liquid nitrogen dispensing device with timer control (A); cryogenic solenoid (B), and complete setup showing guided placement base and LN-dispensing reservoir (C).

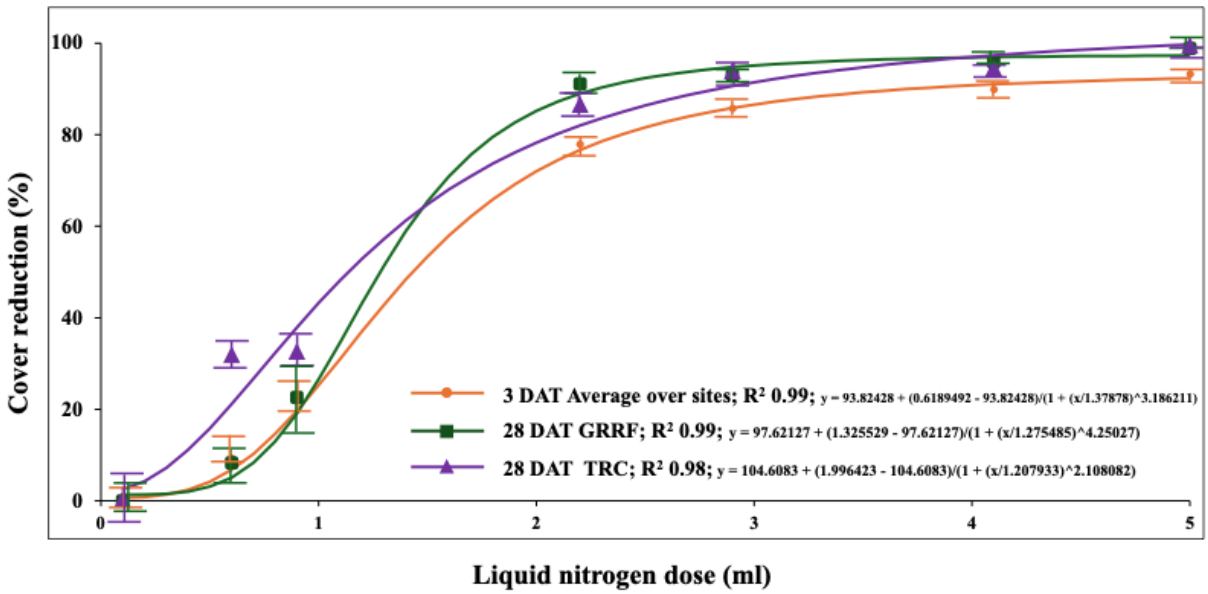

Figure 2. Influence of liquid nitrogen dose on digitally assessed goosegrass green cover reduction at 3 days after treatment (DAT) averaged over both sites and at 28 DAT at each site compared to initial coverage.

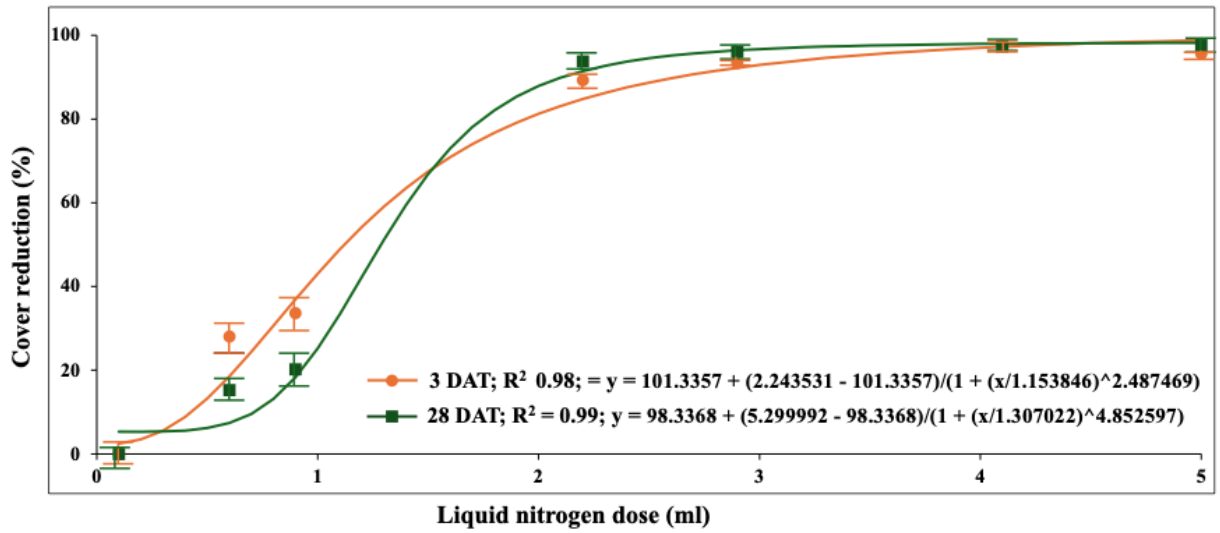

Figure 3. Influence of liquid nitrogen dose on digitally assessed annual bluegrass green cover reduction at 3 and 28 days after treatment (DAT) averaged over both sites compared to initial.

Short title: Laser weeding

Response of Annual Bluegrass, Bermudagrass, Creeping Bentgrass, and Smooth Crabgrass to Laser Intensity Levels and Patterns

Juan R. Romero,[1]Navdeep Godara[2], and Shawn D. Askew[3]

[1]Graduate Assistant (ORCID 0009-0002-7456-0054), School of Plant and Environmental Sciences, Virginia Polytechnic Institute and State University; [2]Graduate Assistant (ORCID 0000-0002-1452-5225), School of Plant and Environmental Sciences, Virginia Polytechnic Institute and State University; and [3]Professor (ORCID 0000-0002-9515-9502), School of Plant and Environmental Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA

Author for correspondence: Shawn D Askew, Professor, School of Plant and Environmental Sciences, Virginia Polytechnic Institute and State University, 675 Old Glade Road, Blacksburg, VA 24061

E-mail: saskew@vt.edu

Abstract

Laser weed control is an emerging non-chemical technology made feasible by recent advances in artificial intelligence and automation. This research evaluated the response of four turf and weed species to varying levels and patterns of laser intensity to determine practical applications of laser weeding in turfgrass systems. Field experiments were conducted from July 2024 to March 2025 on research fairways in Blacksburg, VA, using a 10 W diode laser in spiral patterns with varying pattern-averaged energy densities (PAED). Two studies were implemented: one evaluated increasing energy intensity, and the other assessed combinations of line spacing, PAED, and number of passes in a factorial design. Line spacing significantly influenced weed control efficacy, with 4-mm spacing improving green cover reduction by up to 10% over denser patterns at the same PAED. Bermudagrass (*Cynodon dactylon*) recovered fully within 24 days post-treatment, while creeping bentgrass (*Agrostis stolonifera*) showed prolonged injury at higher intensities and wider spacings. These results demonstrate that laser weeding is feasible in turfgrass systems, especially with optimized energy and pattern configurations, and highlight the need for pattern customization to balance weed control with turfgrass safety.

Nomenclature: Laser; intensity; energy; diode; turfgrass; weeds; crabgrass, *Digitaria spp;* bermudagrass, *Cynodon dactylon*; creeping bentgrass, *Agrostis stolonifera*; annual bluegrass, *Poa annua*; new technologies for weed control; organic treatments; artificial intelligence (AI).

Key words: Laser weeding, turfgrass, weed control, organic treatments

Introduction

The need for alternative weed control methods has increased due to restrictive pesticide regulations, complex registration procedures, and additional legislative constraints imposed by the Food Quality Protection Act and the Endangered Species Act (Dayan et al. 2009; Duzy et al. 2023; Loddo et al. 2021). The widespread herbicide resistance among problematic weed populations further limits the effectiveness of traditional chemical control strategies in turfgrass (Brosnan et al. 2020; McCurdy et al. 2023). Growing public concern about environmental sustainability and potential health risks associated with synthetic herbicides (Li et al. 2014) further underscores the demand for innovative, non-chemical alternatives, particularly in residential, recreational, and urban turfgrass environments where public exposure is significant (Hahn et al. 2020; Md Meftaul et al. 2020).

Laser weed control technology has become feasible with recent advancements in artificial intelligence (AI) and machine vision, allowing real-time weed identification while precisely targeting the plant meristems (Rakhmatulin et al. 2021). This method functions by directing concentrated light energy onto weeds, inflicting thermal damage that either stunts their growth or causes their termination. Laser weeding involves raising the temperature of targeted plant parts, like the apical meristem or stem, to lethal levels, which disrupts cell integrity and halts essential biological processes (Andreasen et al. 2022; Heisel et al. 2002; Mathiassen et al. 2006; Mwitta et al. 2022). Laser weed control utilizes machine learning algorithms to precisely target individual weed seedlings without damaging crops (Carbon Robotics 2025). Carbon Robotics (Seattle, WA) manufactures equipment featuring arrays of 30, 150-Watt CO_2 lasers coupled with 42 high-resolution AI-driven cameras for accurate weed discrimination (Carbon Robotics, 2025). Another company, Weedbot developed Lumina, a laser weeder prototype that uses AI for weed

recognition and blue lasers for targeting weeds and can operate up to 1.5 Km hr^{-1} (WeedBot, n.d.). Earth Rover developed CLAWS™, which integrates AI-driven machine vision with eight cameras and Lightweeder™ modules to target weeds' meristem using concentrated blue light. This system is battery and solar-powered and operates autonomously (European Space Agency, n.d.).

Laser weeding technology presents both advantages and limitations for weed management. In a recent survey of European stakeholders, key benefits identified by participants included reduced labor requirements, high precision in weed targeting, and environmental sustainability (Tran et al. 2023). Conversely, the technology still faces several challenges, such as high energy consumption, a narrow window for targeting weed seedlings, limited operational speed of 4-6 km hr^{-1}, and substantial initial investment costs (Andreasen et al., n.d.). In turfgrass settings, weed management presents distinct challenges compared to production agriculture. Turfgrass weeds are often treated at growth stages significantly more advanced than those targeted in cropping systems. For example, the recommended growth stages of smooth crabgrass [*Digitaria ischaemum* (Schreb) Schreb. ex Muhl] control with Callisto (Mesotrione) at 140 g ai ha^{-1}, in production agriculture are 1-6 leaf (Syngenta, n.d.), while the crabgrass is usually targeted with Tenacity® (Mesotrione) at 175 g ai ha^{-1} in turf at the 3-tiller stage or beyond. Targeting more mature weeds can require more laser energy. Research by Coleman et al. (2020) demonstrated that high-energy dosages (76.4 J mm^{-2}) effectively controlled annual ryegrass (*Lolium rigidum* Gaudin) at early stages but failed to achieve adequate control at mid to late tillering stages. Additionally, Rakhmatulin and Heisel (2008) reported that common lambsquarters (*Chenopodium album* L. Cheal) and wild mustard (*Sinapis arvensis* L.) regrowth after stems being cut with a laser treatment at late growth stage, remarking the importance of

targeting stems as close as possible to the ground or targeting weeds at the seedling stage (Andreasen et al. 2022).

Mature weeds have greater shoot biomass, increased numbers of meristems, and enhanced tolerance to mechanical disruptions, presenting significant hurdles for laser weed management (Sugiyama 2005). For instance, smooth crabgrass and goosegrass [*Eleusine indica* (L.) Gaertn.] can tolerate mowing heights as low as 1.2 cm while surviving in rosette patterns in which a mature plant can develop over a dozen tillers in summer (Abbey et al. 2022). Although laser weeding through rapid energy bursts has proven effective in controlling small seedlings in production crops, its use for managing mature weeds and its effects on turfgrass tolerance have not yet been investigated. Thus, optimizing laser parameters, including energy intensity, application pattern, and treatment frequency, is critical to effectively manage mature turfgrass weeds without negatively affecting desirable turfgrass.

Both laser energy quantity and pattern would be expected to influence weed control because parameter changes will lead to modifications in intensity. By optimizing these parameters, this research seeks to reduce the time and energy needed to control key weeds in turfgrass and evaluate turf recovery rates. This work is based on the assumption that equipment similar to machines already commercialized in production agriculture could likewise be used to apply laser energy directly to targeted weeds in turfgrass systems. In most production agriculture systems, laser weeding is performed by applying energy to a single point on individual weed seedlings, typically at the apical meristem, using stationary or pulsed delivery systems (Mathiassen et al. 2006; Heisel et al. 2002). This approach is effective at early growth stages but less applicable to turfgrass settings, where weeds are often mature, low-growing, and embedded within a dense canopy. In contrast, our proposed method involves delivering laser energy via a

continuously moving laser head over the weed-infested turf surface. This movement results in a distinct spatial and temporal energy distribution not addressed by previous single-point applications. To quantify this dynamic delivery system, we introduced the concept of laser pattern-averaged energy density (PAED), which integrates energy, movement, and spacing parameters into a single metric. Expressed in J cm^{-2} to represent spatially averaged energy across the treated area. PAED allows us to compare and optimize laser dose delivery across treatments in a way that is both reproducible and applicable to complex turfgrass environments. The objectives of our research were to develop a method to deliver laser energy to turfgrass and weed species. This research aims to address significant knowledge gaps regarding the practical application of laser weed technology in turfgrass. Specifically, to identify optimal laser application parameters for effectively targeting mature weeds, reduce the energy and time required for weed control, and evaluate turfgrass recovery post-treatment. The objectives of our research experiments include examining the impacts of varying laser energy levels, line spacing, and one or two passes on weed control of annual bluegrass (*Poa annua* L.) and smooth crabgrass, and turfgrass recovery rates for key turf species, such as bermudagrass (*Cynodon dactylon* L. Pers.) and creeping bentgrass (*Agrostis stolonifera* L.).

Materials and Methods

Weed and Turfgrass Response to Increasing Pattern-Averaged Energy Density

A total of 8 field experiments were conducted to test doses of PAED on four species at two unique sites in space and/or time from July 2024 to March 2025. All experiments were conducted on research fairways (mowed at 13 to 19 mm thrice weekly) at the Turfgrass Research Center (TRC) (37°12'54"N 80°24'46" W) and the Glade Road Research Facility (37°14'03"N

80°26'10" W) in Blacksburg, VA. All species were evaluated in separate studies. Weeds included natural infestations of smooth crabgrass and annual bluegrass. Turfgrasses include bermudagrass, 'Patriot' at Site 1 and 'Latitude 36' at Site 2, and creeping bentgrass, 'L93' at both sites. Each study was implemented as a single-factor randomized complete block design with four replicates, and two trial sites. The single factor consisted of six different levels of pattern-averaged energy density (PAED) achieved by altering operating speed of a 10 W diode laser engraver (Xtool D1, Makeblock Co., Ltd., Shenzhen, China) with a 0.08 mm × 0.06 mm laser dot (Table 1), while consistently applying two passes of a continuous square spiral with lines spaced 2 mm apart (Figure 1B) on 100 cm^2 plots. Levels of PAED, line-specific energy density (LSED) and other treatment parameters are listed in Table 1. Laser PAED is the amount of energy delivered over the total area where a given pattern has been burned and is expressed in Equation 1 as,

$$\text{PAED (J cm}^{-2}) = (e*t)/A \quad [1]$$

where e is laser energy in (W), t is time to treat a given pattern on a given plot in (s), and A is the area of the treated plot in (cm^2). The LSED, which is the amount of energy delivered in each pattern line, is explained in Equation 2 as,

$$\text{LSED (J cm}^{-2}) = (e*t)/A_t \quad [2]$$

where A_t is the ratio of treated area to total area in each plot. These calculations allow comparison of treatment intensities across moving laser patterns and ensure consistent reporting of both total energy exposure and concentrated dose at the point of contact. The diode laser was directed via LightBurn software (LightBurn Software, LLC.; Pasadena, TX). Plot edges were cut before each data assessment with a 1 dm^{-2} metal tubing to avoid lateral growth into the plots from adjacent, nontreated areas. The use of a two-pass pattern with 2-mm line spacing was based

on preliminary experiments, where laser energy delivered in two passes delayed creeping bentgrass recovery compared to one pass and equivalent to three passes (Romero et al. 2023). Digital pictures were collected at 0, 3, 7, 14, 21, and 28 d after treatment (DAT) using a custom lightbox mounted with a digital camera (Canon EOS 5D Mark IV; Tokyo, Japan) and a 100 mm macro lens EF 100 mm f/2.8L (Macro IS USM; Tokyo, Japan) affixed with an exclusion plate with an opening specific to each plot. Digital images were analyzed for green cover based on hue and intensity thresholds via Turf Analyzer (Green Research Services, LLC.; Fayetteville, AR). Green cover data at each assessment date was converted to a percent reduction compared to the initial pretreatment cover. Percentage-cover-reduction data from each species were subjected to ANOVA using PROC GLM in SAS v 9.3 (SAS Institute, NC) with sums of squares partitioned to reflect treatment, trial, and trial by treatment. Trial was considered a random variable in the combined analysis, and mean squares of treatment were tested by mean squares of trial by treatment. Means were separated using Fisher's Protected LSD ($\alpha = 0.05$) and separately by trials if the interaction was significant; otherwise, means were pooled over sites.

Weed and Turfgrass Response to Varied Laser Pattern at Discreet Energy Levels

A total of 8 field experiments were conducted as randomized complete block designs at adjacent sites and times compared to the previous study but employing a 2 x 2 x 3 factorial treatment design (Table 1). The three factors evaluated were two levels of PAED (200 and 400 J/cm^2), three levels of line frequency in a continuous square spiral (1, 2 or 4 mm apart, Figure 1), and the number of times the laser passed over each line (once or twice) (Table 2). Subsequent passes were initiated immediately after completing the entire pattern. The two levels of PAED were based on results of the first experiment. Data collection and statistical analysis were the same as the previous study, although, the ANOVA included additional partitions for the sums of

squares of PAED, pattern line spacing, number of passes, trial, and all possible interactions of these variables. In all cases, significant interactions were presented in lieu of main effects.

Results and Discussion

Weed and Turfgrass Response to Increasing Pattern-Averaged Energy Density

Smooth crabgrass. The interaction of trial by treatment was significant for smooth crabgrass green cover reduction at 3 DAT ($P < 0.0001$) and 28 DAT ($P = 0.0091$) (Figure 2). At 3 DAT, both sites exhibited rapid discoloration, with cover reduction exceeding 90% at 160 J cm^{-2} PAED. By 220 J cm^{-2}, responses had plateaued near 95% at both locations, indicating consistent acute injury across trials at higher dosages. However, differential recovery was observed by 28 DAT. At Site 1, green cover reduction reached 93% at the maximum dose of 410 J cm^{-2}, while Site 2 maintained 82% reduction, suggesting less persistent injury under those conditions. These trial-dependent outcomes may reflect differences in crabgrass maturity (2-4 tillers at Site 1 vs. 4-6 tillers at Site 2), edaphic factors, or irrigation regimes. Nonetheless, the level of suppression observed is comparable to that of postemergence herbicides such as fenoxaprop (Brewer et al. 2017), mesotrione (Goncalves et al. 2021; Goddard et al. 2021), quinclorac (Willis et al. 2006), and topramezone (Cox et al. 2017). In addition, the conditions of this study, although optimized for tracking fluctuations in weed green cover via digital image analysis, preclude turfgrass competition with weeds, which could have enhanced weed mortality or reduced weed recovery (Koo et al. 2022).

Annual bluegrass. The trial by treatment interaction was significant ($P = 0.0016$) for annual bluegrass control 3 DAT, while only the treatment main effect remained at 28 DAT ($P = 0.0014$)

(Figure 3). The source of the trial interaction at 3 DAT may lie in higher green cover reduction of annual bluegrass at lower PAED doses (< 70) at Site 1. For example, 50% green cover reduction required 55 J cm^{-2} and 43 J cm^{-2} PAED at Sites 1 and 2, respectively, 3 DAT (Figure 3). At 28 DAT, annual bluegrass recovered from laser treatments consistently across trials leading to 50% green cover reduction by 200 J cm^{-2} PAED and 80% reduction at 340 J cm^{-2} PAED. Thus, annual bluegrass was seen as an excellent candidate to evaluate potential benefits of pattern manipulation, which will discussed in the next section. At 410 J cm^{-2} PAED, annual bluegrass cover was reduced 89% at 28 DAT, consistent with better performing herbicides such as foramsulfuron (Willis et al. 2008), trifloxysulfuron (Askew et al. 2013), flazasulfuron (Goddard et al. 2022), glyphosate (Askew et al. 2019), glufosinate (Craft et al. 2023), methiozolin (Askew and McNulty 2014) and endothall (Peppers et al. 2025). Alternative strategies for annual bluegrass control are important to address herbicide-resistant biotypes that have become persistent in recent years (Bowling et al. 2024; McCurdy et al. 2023). These data suggest laser energy could be an effective measure to support this industry need.

Bermudagrass. Laser energy rapidly discolored bermudagrass in response to increasing PAED ($P = 0.0005$) consistently across trials, as evidenced by an insignificant treatment by trial interaction 3 DAT ($P > 0.05$) (Figure 4). Bermudagrass discoloration peaked at 90% following treatment of 180 J cm^{-2} PAED or more 3 DAT (Figure 4). Despite initial discoloration, bermudagrass recovered rapidly at both locations, although significantly ($P < 0.05$) slower at Site 1 where green cover reduction 14 DAT by 410 J cm^{-2} PAED was 44% compared to only 27% by this energy dose at Site 2 (Figure 4). at 28 DAT, bermudagrass had recovered entirely independently of the energy level. Bermudagrass also recovered from thermal treatments such as hot water and direct flame more rapidly than other turfgrasses (Anonymous 2021). Although green cover

reduction of turfgrass at this scale would not normally be commercially acceptable (Patton et al. 2010), laser applications made by machine-vision would primarily direct radiation to targeted weeds. Given that bermudagrass recovers more rapidly than both smooth crabgrass (Figure 2) and annual bluegrass (Figure 3), the prospects of targeted weed control in turfgrass with lasers are rendered more plausible.

Creeping bentgrass. The interaction of trial by treatment was significant for creeping bentgrass green cover reduction at 3 DAT ($P = 0.0051$) and 28 DAT ($P < 0.05$) (Figure 5). By 3 DAT, both sites exhibited strong initial responses, with green cover reduction reaching 91% at 160 J cm^{-2} PAED at Site 1 and 90% at Site 2 — indicating that creeping bentgrass is highly sensitive to laser energy. At 28 DAT, creeping bentgrass injury persisted at Site 1 with a 59% cover reduction at the maximum 410 J cm^{-2} dose, while Site 2 exhibited a reduced response of 65%, suggesting slightly less recovery under those trial conditions. Although environmental factors such as soil moisture were not recorded, they likely contributed to observed site-dependent effects, consistent with results from other thermal weed control studies (Anonymous 2021). Despite some variability, creeping bentgrass showed relatively high susceptibility and limited recovery compared to smooth crabgrass and annual bluegrass. While our study design does not support direct species comparisons, general trends suggest that C4 species like crabgrass may recover more robustly than C3 grasses such as creeping bentgrass. Prior research in agronomic systems has shown that species-specific traits and growth stages significantly influence laser efficacy (Andreasen et al. 2024), a finding further reinforced in this turfgrass study.

Weed and Turfgrass Response to Varied Laser Pattern at Discreet Energy Levels

The main effect of pattern line spacing was the only significant effect ($P < 0.05$) for smooth crabgrass green cover reduction 3 DAT (Table 2). By increasing line spacing from 1 mm

to 2 or 4 mm, smooth crabgrass cover reduction was increased by 8 to 10%. This phenomenon was also exhibited in the significant interaction of trial by pattern-averaged energy density by pattern line spacing ($P < 0.05$) where the 1-mm spacing reduced smooth crabgrass cover 28 DAT less than the 4 mm spacing at both sites when 200 J cm^{-2} PAED was applied and at Site 2 when 400 J cm^{-2} PAED was applied (Table 2). This pattern influence likely occurred because the 4-mm line spacing had line-specific energy densities that were four times greater than the 1-mm line spacing (Table 1). Within a given site, the 4-mm line spacing applied at 200 J cm^{-2} PAED consistently reduced smooth crabgrass, equivalent to 400 J cm^{-2} PAED applied in a pattern of 1-mm line spacing (Table 2). This is the first report regarding how altering laser patterns can change plant responses across PAED levels. In prior research conducted in production agriculture, only seedling weeds have been targeted (Heisel et al. 2001; Yaseen and Long 2024). A relevant comparison between the laser pattern assessments in this study and previous work can be drawn from Mathiassen et al. (2006), who demonstrated that increasing laser spot diameter (from 0.9 mm to 2.4 mm) significantly reduced weed control efficacy at a given energy dose, due to the lower energy density delivered to the apical meristem.

Annual bluegrass cover reduction exhibited a trial by pattern line spacing interaction due to differences in the performance of the 1-mm spacing between sites at 3 DAT (Table 2). At Site 2, annual bluegrass cover was reduced less by the 1-mm spacing while cover reduction was not dependent on spacing at Site 1 (Table 2). At 28 DAT, annual bluegrass cover reduction exhibited only a line spacing main effect with a stepwise increase in cover reduction as line spacing increased from 1 mm to 4 mm. These data suggest that line spacing strongly influences weed control and potentially could be optimized beyond the 4-mm spacing assessed here. Future research should evaluate an expanded range of line spacings to determine if further optimization

is possible. As in the previous study, laser weed control can be comparable to leading herbicides (Brosnan et al. 2013; Flessner et al. 2017), given the appropriate laser pattern and intensity.

Both turfgrasses exhibited rapid recovery from laser treatments but on different temporal scales. Thus, rather than report data at discreet assessment times as was done for the weeds, it seemed more appropriate to calculate maximum cover reduction and time to complete recovery (bermudagrass) or percentage recovery at 28 DAT (creeping bentgrass). The interaction of PAED by line spacing was significant for maximum bermudagrass cover reduction ($P < 0.05$) (Table 3). At the lower energy level, the 1-mm spacing reduced bermudagrass green cover slightly less than the 4-mm spacing, while differences between line spacings were not evident when the PAED was increased from 200 J cm^{-2} to 400 J cm^{-2} (Table 3). Bermudagrass recovery time varied by line spacing but was dependent on site ($P = 0.0029$ Table 3). At Site 1, it took 3 additional days for bermudagrass to recover following the 4-mm spacing, but this trend was not evident at Site 2. Bermudagrass recovery required 21 to 24 d depending on site and line spacing. Although similar recovery durations have been noted following herbicide injury (Brewer et al. 2017; Cox et al. 2017), such durations are generally deemed unacceptable. Thus, targeted weed control via machine vision (Xie et al. 2021) will be important to improve selectivity of laser weed control in turfgrass.

Maximum cover reduction for creeping bentgrass was influenced by a line-spacing-by-pass-number interaction ($P < 0.05$) and a site-by-line-spacing interaction ($P < 0.05$) (Table 3). Creeping bentgrass cover was maximally reduced 79 to 91% depending on pass number, line spacing, and site. When one pass was applied, the LSED is the same as for two passes (Table 1), but all of the energy is delivered in a single pass rather than split between the two passes. This led to a step-wise increase in maximum creeping bentgrass cover reduction with line spacing at

one pass while both 2- and 4-mm line spacings maximally reduced creeping bentgrass cover equivalently and more than the 1-mm spacing when two passes were applied (Table 3). At both sites, the 1-mm line spacing caused maximum cover reductions that were less than those of the 2 mm and 4 mm line spacings. Creeping bentgrass recovery at 28 DAT exhibited an interaction between trial and line spacing ($P < 0.05$) (Table 3) similar to that of maximum cover reduction. When 1-mm spacing was used, creeping bentgrass recovered 47 and 65% of its initial cover at 28 DAT (Table 3). For the 4-mm spacing, recovery was only 37 to 42%, depending on site (Table 3).

These data show that line spacing and PAED of a continuous square spiral of laser radiation influences plant responses for both weed and turfgrasses. Likewise, the effectiveness of laser treatments observed in this study is consistent with previous research, highlighting the ability of lasers to disrupt critical plant tissues through focused energy application, thereby minimizing environmental disturbance like chemical or mechanical methods (Yaseen & Long 2024; Andreasen et al. 2022). Trends in the data suggest that both site conditions and targeted plant species may influence plant response to laser energy, but limitations in our design preclude specific inferences related to environmental conditions or species. Laser performance for weed control has been shown to depend on laser parameters and weed species traits (Mathiassen et al. 2006), though environmental site conditions remain an area requiring further exploration.

Integrating autonomous robots could enhance the practicality of laser weeding within turfgrass environments, mainly due to time constraints. Autonomous robotic systems, equipped with advanced navigation and real-time identification capabilities, might reduce labor requirements while reducing the use of chemical herbicides, following a trend that calls for less pesticide usage. However, laser weeding presents certain challenges that require attention for

broader adoption. Variability in weed species characteristics, particularly stem thickness and resilience, necessitates precise calibration of energy density (Heisel et al. 2002; Mathiassen et al. 2006). The scalability and speed of current laser weeding technology present additional challenges, with high initial costs and operational speeds potentially limiting widespread use in larger turf areas. Previous studies suggest that deploying robotic fleets could mitigate some scalability issues (Yaseen & Long 2024). Safety considerations, including potential fire hazards in dry turf conditions, demand the incorporation of advanced sensor technologies and robust safety protocols, as recommended by earlier studies (Andreasen et al., 2022). Addressing these concerns is vital for safe, effective, and widespread use of laser weeding.

This research demonstrates that laser parameters can be strategically customized to improve time and energy efficiency while maintaining effective weed control. This work is the first to report the influence of laser patterns on mature weed control and shows that changes in pattern line spacing can influence weed control, potentially reducing energy requirements by half. Future studies will investigate the influence of environmental conditions such as temperature and humidity and expand the exploration of laser application patterns. Additionally, further work is needed to assess a broader spectrum of weed and turf species, including different growth stages. Improving weed detection algorithms will also be critical to boosting precision and reducing costs. By addressing these technical and biological challenges, laser weeding is well-positioned to become useful tool in sustainable turfgrass management.

Competing Interests

The authors declare none.

Funding

This research was partially funded by The Virginia Agricultural Council in association with the Virginia Turfgrass Foundation (Project Number 858).

References

Abbey T, Landschoot P, Delvalle T (2022) Lawn and turfgrass weeds: Smooth crabgrass and large crabgrass. Penn State Extension. Available at: https://extension.psu.edu/lawn-and-turfgrass-weeds-smooth-crabgrass-and-large-crabgrass (Accessed: [03-09-2025]).

Andreasen C, Saberi M, Rakhmatulin I (n.d.) Weed control with laser beams using autonomous vehicles: pros and cons. WeLaser Project. Available at: https://welaser-project.eu/wp-content/uploads/2021/12/FIRA2021-Andreasen-et-al-.pdf (Accessed: [03-11-2025]).

Andreasen C, Scholle K, Saberi M (2022) Laser weeding with small autonomous vehicles: Friends or foes? Front Agron 4:841086 https://doi.org/10.3389/fagro.2022.841086

Andreasen C, Vlassi E, Salehan N (2024) Laser weeding: Opportunities and challenges for couch grass (Elymus repens (L.) Gould) control. Scientific Reports, 14, 11173. https://doi.org/10.1038/s41598-024-61742-8

Anonymous. (2021) Effects of flaming in turfgrass and weed species.

Askew S, Askew W, Goatley J (2019) Fineleaf Fescue Species and Variety Tolerance to Glyphosate. Weed Technology, 33(1), 185-191. doi:10.1017/wet.2018.65

Askew SD, Goddard JR, Askew WL, Beam JB, Keese RJ (2013) Effect of trifloxysulfuron sodium rate and sequential treatments on transition of overseeded bermudagrass fairways. Int. Turf. Soc. Res. J. 12:689-694.

Askew SD, McNulty BS (2014) Methiozolin and cumyluron for preemergence annual bluegrass (*Poa annua*) control on creeping bentgrass (*Agrostis stolonifera*) putting greens. Weed Technol. 28(3):535-542. doi:10.1614/WT-D-14-00018.1

Bowling B, McCurdy J, De Castro E, Patton A, Brosnan J, Askew S, Breeden G, Elmore M, Gannon T, Concalves C, Kaminski J, Kowalewski A, Liu W, Mattox, C, McCarty B,

McCullough P, McElroy J, McKeithen C, Osburn A, Rogers R, Rutland CA, Tang K, Taylon J, Unruh J, Vargas J, Bagavathiannan M (2024) Multi-state survey to identify suspected resistance to four herbicides and one plant growth regulator in Poa annua. Crop Forage & Turfgrass Mgt. 10, e20300. https://doi.org/10.1002/cft2.20300

Brewer JR, Willis J, Rana SS, Askew SD (2017) Response of six turfgrass species and four weeds to three hppd-inhibiting herbicides. Agron. J. 109(4):1777-1784. doi:10.2134/agronj2016.06.0345

Brewer JR, Askew SD (2021) Investigating low-dose herbicide programs for goosegrass (Eleusine indica) and smooth crabgrass (Digitaria ischaemum) control on creeping bentgrass greens. Weed Technol., 35(4), 604-610. doi:10.1017/wet.2021.55

Brosnan JT, Elmore MT, Bagavathiannan MV (2020) Herbicide-resistant weeds in turfgrass: current status and emerging threats. Weed Technol 34:424–430.

Brosnan JT, Henry GM, Breeden GK, Cooper T, Serensits TJ (2013) Methiozolin efficacy for annual bluegrass control on sand- and soil-based creeping bentgrass putting greens. Weed Technol 27:310–316

Carbon Robotics (2022) Laser weeding technology. Available at: https://www.carbonrobotics.com (Accessed: [03-10-2025]).

Coleman G, Betters C, Squires C, Walsh M (2021) Low energy laser treatments control annual ryegrass (*Lolium rigidum*). Front Agron 2:601542.

Cox MC, Rana SS, Brewer JR, Askew SD (2017) Goosegrass and bermudagrass response to rates and tank mixtures of topramezone and triclopyr. Crop Sci. 57(S1):S310-S321. doi:10.2135/cropsci2016.05.0439

Craft JM, Godara N, Derr JF, Nichols AD, McCurdy JD, Richard MP, Askew SD (2023) Regional response of zoysiagrass turf to glufosinate and glyphosate applied during postdormancy transition based on accumulated heat units. Weed Technology. 2023;37(4):361-367. doi:10.1017/wet.2023.46

Dayan FE, Cantrell CL, Duke SO (2009) Natural products in crop protection. Bioorg Med Chem 17:4022–4034

Duzy LM, Campana DJ, Brain R (2023) Agroeconomic costs for meeting the Environmental Protection Agency's mitigation menu approach to pesticide regulation. Agric Environ Lett 8:e20119

European Space Agency (n.d.) Earth Rover: Concentrated Light Autonomous Weeding and Scouting. Retrieved April 18, 2025, from https://business.esa.int/projects/earth-rover-concentrated-light-autonomous-weeding-and-scouting

Elmore M, Tuck DP (n.d.) Crabgrass and Goosegrass Identification and Control in Cool-Season Turfgrass for Professionals. Available at: https://njaes.rutgers.edu/fs1347/ (Accessed: [03-10-2025]).

Flessner ML, McElroy JS, McCurdy JD (2017) Annual Bluegrass (Poa annua) Control with Methiozolin and Nutrient Tank-Mixtures. Weed Technology. 31(5):761-768. doi:10.1017/wet.2017.40

Goddard MJR, Goncalves CG, Askew SD (2021) Simulated controlled-release mesotrione for turfgrass tolerance and weed control. Weed Technol., 35(4), 582-588. doi:10.1017/wet.2021.19

Goddard MJ, Gonçalves CG, Askew SD (2022) Selective perennial ryegrass control in creeping bentgrass with flazasulfuron. Int. Turfgrass Res. Soc. J., 14(1), 742-746

Goncalves CG, Ricker DB, Askew SD (2021) Perennial ryegrass phytotoxicity increases with mesotrione rate and growth-promoting environmental conditions. Crop Sci., 61(5), 3155-3163. doi:10.1002/csc2.20407

Koo D, Goncalves C, Askew SD (2022) Lolium arundinaceum leaf and root developmental temperatures influence its allelopathic potency on Poa annua. Int. Turfgrass Res. Soc. J., 14(1), 787-790.

McCurdy JD, Bowling RGG, de Castro EB, Patton AJ, Kowalewski AR, Mattox CM, Bagavathiannan MV (2023) Developing and implementing a sustainable, integrated weed management program for herbicide-resistant Poa annua in turfgrass. Crop Forage & Turf. Mgt., 9(1), 13 pages. https://doi.org/10.1002/cft2.20225

Li Y Zhang C, Yin Y, Cui F, Cai J, Chen Z, Jin Y, Robson MG, Li M, Ren Y, Huang X, Hu R (2014) Neurological effects of pesticide use among farmers in China. Int J Environ Res Public Health 11:3995–4006

Loddo D, McElroy JS, Giannini V (2021) Problems and perspectives in weed management. Ital J Agron 16:1854

Mathiassen SK, Bak T, Christensen S, Kudsk P (2006) The effect of laser treatment as a weed control method. Biosyst Eng 95:497–505.

McCurdy JD, Bowling RG, Patton AJ, Kowalewski AR, Mattox CM, Brosnan JT, Ervin DE, Askew SD, Goncalves CG, Elmore MT, McElroy JS, McNally BC, Pritchard BD, Kaminski JE, Bagavathiannan MV (2023) Developing and implementing a sustainable, integrated weed management program for herbicide-resistant Poa annua in turfgrass. Crop Forage Turfgrass Manag 9:e20225.

Md Meftaul I, Venkateswarlu K, Dharmarajan R, Annamalai P, Megharaj M (2020) Pesticides in the urban environment: a potential threat that knocks at the door. Sci Total Environ 711:134612

Mwitta C, Rains GC, Prostko E (2022) Evaluation of diode laser treatments to manage weeds in row crops. Agronomy 12:2681

Nature Robots (n.d.) Modular autonomy design-in software platform. Available at: https://naturerobots.com/en/products/ (Accessed: [insert date you accessed the page]).

Hahn D, Sallenave R, Pornaro C, Leinauer B (2020) Managing cool-season turfgrass without herbicides: optimizing maintenance practices to control weeds. Crop Sci 60:2204–2220

Heisel T, Schou J, Andreasen C, Christensen S (2002) Using laser to cut and measure thickness of Beta vulgaris L. and Solanum nigrum L. stems. Weed Res 42:242–248

Heisel T, Schou J, Christensen S, Andreasen (2001) Cutting weeds with a CO2 laser. Weed Research, 41(1), 19-29. https://doi.org/10.1046/j.1365-3180.2001.00212.x

Patton AJ, Trappe JM, Strahan RE, Beasley JS. Sulfonylurea Herbicide Safety on Newly Sprigged Bermudagrass and Seashore Paspalum. Weed Technology. 2010;24(3):342-348. doi:10.1614/WT-D-09-00018.1

Peppers JM, Askew SD (2025) Evaluation of spring-applied endothall for annual bluegrass control in warm-season turf. Weed Technol. 2025 Jan;39:e29.

Rakhmatulin I, Andreasen C (2020) A concept of a compact and inexpensive device for controlling weeds with laser beams. Agronomy 10:1616

Rakhmatulin I, Kamilaris A, Andreasen C (2021) Deep neural networks to detect weeds from crops in agricultural environments in real-time: a review. Remote Sens 13:4486

Romero JR, Godara N, Askew SD (2025) Is Laser Energy Practical for Weed Management in Turfgrass? Southern Weed Science Society (SWSS) Charleston, South Carolina.

Sugiyama S (2005) Relative contribution of meristem activities and specific leaf area to shoot relative growth rate in C3 grass species. Funct Ecol 19:925–931

Syngenta (n.d.) CALLISTO 480SC herbicide label. Available at: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://assets.syngenta.ca/pdf/ca/labels/CALLISTO_480SC_27833_en_pamphlet.pdf (Accessed: [03-09-2025]).

Tran D, Schouteten JJ, Degieter M (2023) European stakeholders' perspectives on implementation potential of precision weed control: the case of autonomous vehicles with laser treatment. Precis Agric 24:2200–2222

WeedBot (n.d.) WeedBot weeding technology. Available at: https://weedbot.eu/weedbot-technology/ (Accessed: [03-09-2025]).

Willis JB, Ricker DB, Askew SD (2008) 'Riviera' bermudagrass response to pre-seeding applications of sulfonylurea herbicides. App. Turf. Sci. 10.1094/ATS-2008-0916-01-RS.

S Xie, C Hu, M Bagavathiannan, Song D (2021) Toward Robotic Weed Control: Detection of Nutsedge Weed in Bermudagrass Turf Using Inaccurate and Insufficient Training Data. in IEEE Robotics and Automation Letters, vol. 6, no. 4, pp. 7365-7372, doi: 10.1109/LRA.2021.3098012

Yaseen M, Long JM (2024) Laser weeding technology in cropping systems: a comprehensive review. Agronomy, 14(10), 2253

Table 1. Parameters of laser energy and varying pattern for two studies conducted to influence smooth crabgrass, annual bluegrass, bermudagrass and creeping bentgrass green cover over time[a].

Treatment	Pattern spacing	Passes	Treatment time	Pattern-averaged energy density[b]	Line-specific energy density[b]	Area treated by the laser
	mm		s dm^{-2}	---------- J cm^{-2} ----------		%
Study 1						
1	-	-	0	0	0	0
2	2	2	4160	416	11429	3.64
3	2	2	1560	156	4286	3.64
4	2	2	960	96	2637	3.64
5	2	2	693	69	1905	3.64
6	2	2	543	54	1491	3.64
Study 2						
1	1	1	2000	200	2801	7.14
2	2	1	2000	200	5495	3.64
3	4	1	2000	200	10584	1.89
4	1	1	4000	400	5602	7.14
5	2	1	4000	400	10989	3.64
6	4	1	4000	400	21195	1.89
7	1	2	2000	200	2802	7.14
8	2	2	2000	200	5496	3.64
9	4	2	2000	200	10584	1.89
10	1	2	4000	400	5602	7.14
11	2	2	4000	400	10990	3.64
12	4	2	4000	400	21664	1.89

[a]Laser spot diameter was 0.08 mm × 0.06 mm from a 10 W diode laser and delivered a continuous square spiral pattern to 100 cm^2 plots in all cases. For patterns that received 2 passes, the second pass was initiated immediately after the first pattern was finished.
[b]Laser intensity was based on the pattern-averaged energy density (PAED) calculated as PAED (J cm^{-2}) = $(e*t)/A$ where e is laser energy (W), t is time to treat a given pattern on a given plot (s), and A is the area of the treated plot (cm^2). The line-specific energy density describes radiation actually delivered to each line in a given pattern and is calculated as LSED (J cm^{-2}) = $(e*t)/A_t$ where A_t is the ratio of treated area to total area in each plot.

Table 2. Main effect of laser pattern line spacing on smooth crabgrass and annual bluegrass green cover reduction at 3 days after treatment (DAT) and 28 DAT, respectively; Interaction of trial by pattern-averaged energy density (PAED) by pattern line spacing for smooth crabgrass at 28 DAT; and interaction of trial by pattern line spacing for annual bluegrass green cover reduction at 3 DAT[a].

	Smooth crabgrass					Annual bluegrass		
		PAED 200[b] at 28 DAT		PAED 400[b] at 28 DAT		3 DAT		
Spacing (mm)	3 DAT	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	28 DAT
1	85b	61b	58c	84b	62b	94a	89b	39c
2	94a	83a	64b	89a	86a	95a	93a	55b
4	95a	90a	69a	85ab	87a	95a	93a	69a

[a]Laser spot diameter was 0.08 mm × 0.06 mm from a 10 W diode laser and delivered a continuous square spiral pattern to 100 cm^2 plots in all cases. For patterns that received 2 passes, the second pass was initiated immediately after the first pattern was finished.
[b]Laser intensity was based on the pattern-averaged energy density (PAED) calculated as PAED (J cm^{-2}) = $(e*t)/A$ where e is laser energy in (W), t is time to treat a given pattern on a given plot (s), and A is the area of the treated plot (cm^2). The line-specific energy density describes radiation actually delivered to each line in a given pattern and is calculated as LSED (J cm^{-2}) = $(e*t)/A_t$ where A_t is the ratio of treated area to total area in each plot.
[c]Means followed by the same letter within each column are not different based on Fisher's protected LSD ($\alpha = 0.05$).

Table 3. Interaction of laser pattern-averaged energy density (PAED) by pattern line spacing on maximum bermudagrass green cover reduction; interaction of trial by pattern line spacing for bermudagrass time to complete recovery, creeping bentgrass maximum cover reduction, and creeping bentgrass recovery at 28 days after treatment (DAT); and interaction of pattern passes by pattern line spacing on creeping bentgrass maximum cover reduction[a].

	Bermudagrass				Bentgrass					
	Max reduction (%)		Time to recover (d)		Max reduction (%)		Max reduction (%)		Recovery at 28 DAT (%)	
Spacing (mm)	PAED[b] 200	PAED[b] 400	Site 1	Site 2	One pass	Two passes	Site 1	Site 2	Site 1	Site 2
1	90b*	96a*[c]	21b	24a	81b	79b	82b	79b	47a	65a
2	95a	96a	21b	24a	86ab	86a	87ab	85a	41b	47b
4	97a	98a	24a	24a	91a	88a	91a	88a	42b	37c

[a]Laser spot diameter was 0.08 mm × 0.06 mm from a 10 W diode laser and delivered a continuous square spiral to 100 cm^2 plots in all cases. For patterns that received 2 passes, the second pass was initiated immediately after the first pattern was finished.
[b]Laser intensity was based on the pattern-averaged energy density (PAED) calculated as PAED (J cm^{-2}) = $(e*t)/A$ where e is laser energy (W), t is time to treat a given pattern on a given plot (s), and A is the area of the treated plot (cm^2). The line-specific energy density describes radiation actually delivered to each line in a given pattern and is calculated as LSED (J cm^{-2}) = $(e*t)/A_t$ where A_t is the ratio of treated area to total area in each plot.
[c]Means followed by the same letter within each column are not different based on Fisher's protected LSD ($\alpha = 0.05$). A "*" indicates differences between PAED or number of passes within a given level of pattern line spacing.

Figure 1. Schematic representation of a continuous square spiral pattern (A) 1 mm spacing (B) 2 mm spacing (C) 4 mm spacing between lines (D) Example of a 2 mm spacing pattern burned in a smooth crabgrass weed.

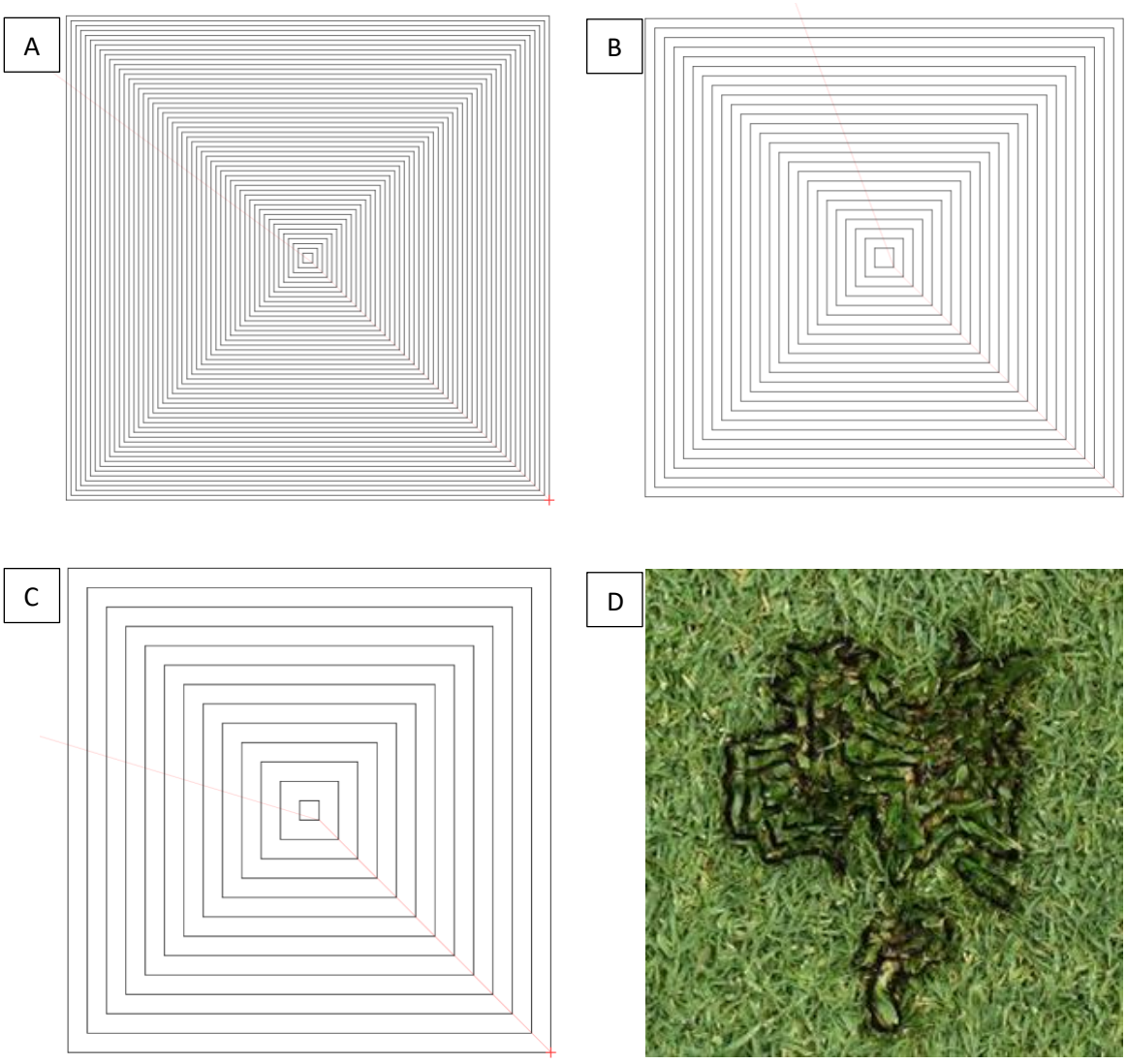

Figure 2. (study #1) Influence of laser intensity levels achieved by different speeds on digitally assessed smooth crabgrass green cover reduction compared to the initial cover, at 3 days after treatment (DAT) and 28 DAT by site.

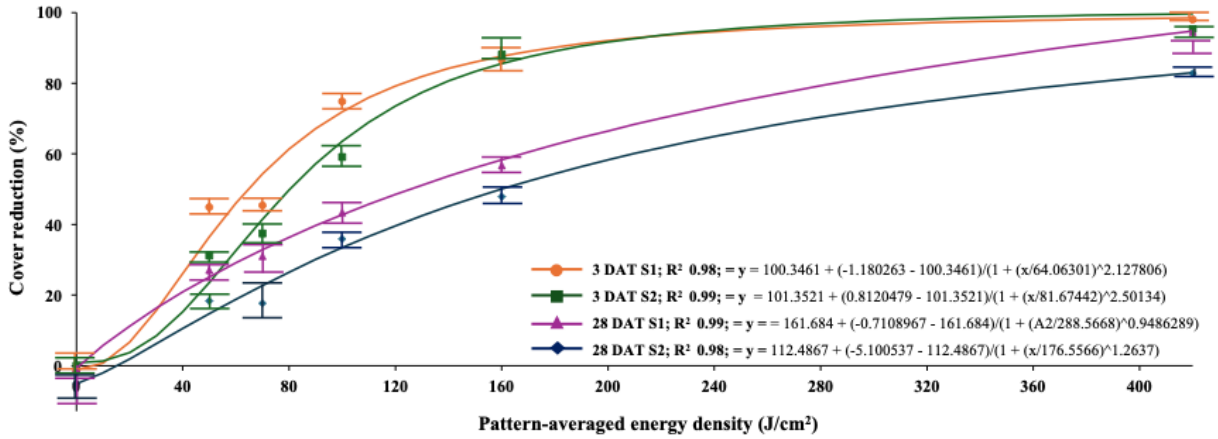

Figure 3. (study #1) Influence of laser intensity levels achieved by different speeds on digitally assessed annual bluegrass green cover reduction compared to the initial cover, at 3 days after treatment (DAT) by sites (S1 and S2) and average over sites at 28 DAT.

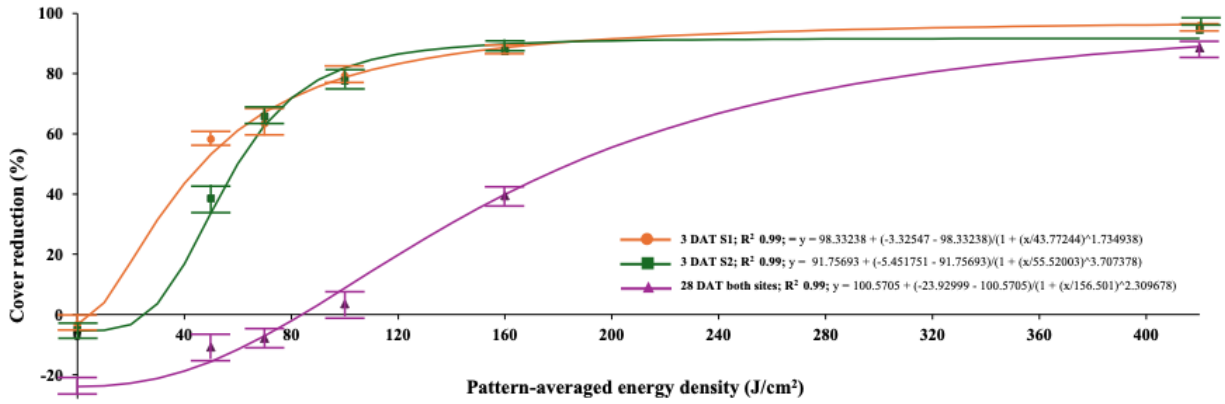

Figure 4. (study #1) Influence of laser intensity levels achieved by different speeds on digitally assessed bermudagrass green cover reduction compared to the initial cover, at 3 days after treatment (DAT) average over sites and 14 DAT by sites (S1 and S2).

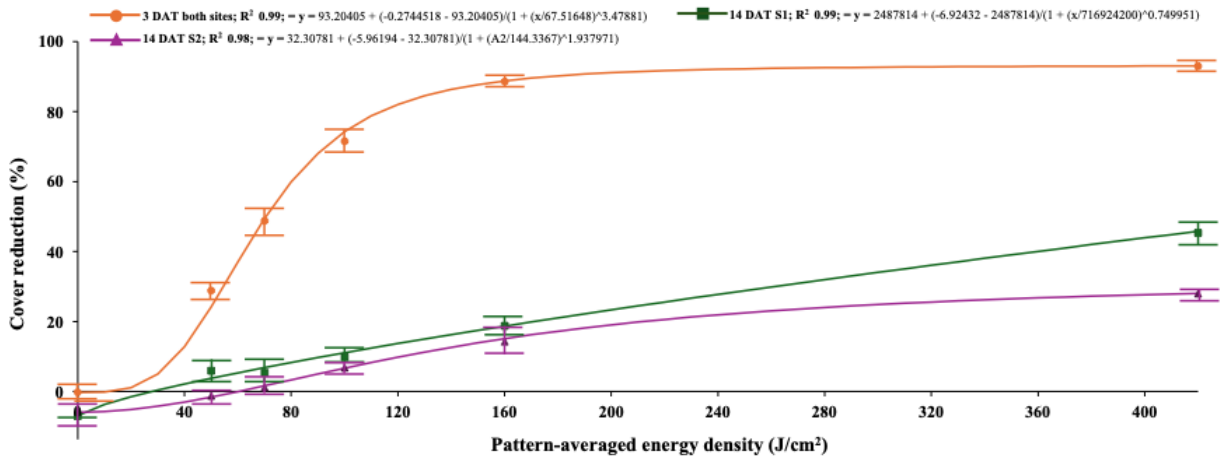

Figure 5. (study #1) Influence of laser intensity levels achieved by different speeds on digitally assessed creeping bentgrass green cover reduction compared to the initial cover, at 3 days after treatment (DAT) and 28 DAT by site.