ABSTRACT

HUNTER III, JOSEPH EARL. Integration of Unmanned Aerial Vehicles (UAVs) for Remote-Sensing and Spray Applications for Weed Management. (Under the direction of Dr. Ramon Leon).

The common characteristic of weeds of having patchy spatial distributions provides the opportunity for site-specific management. Site-specific weed management has been proven to be a viable alternative to reduce broadcast weed control and consequently decreasing herbicide usage and improving environmental quality. Unmanned aerial vehicles (UAVs) offer a new management platform that can account for spatial variability in weed populations to conduct site-specific management. UAVs can be used to collect imagery for monitoring and decision-making purposes as well as to conduct aerial pesticide applications. In recent times, UAVs have become commercially available for both agricultural implications. Limited research has been conducted concerning aerial pesticide applications from UAVs. Two independent field studies were conducted to evaluate the feasibility of integrating UAVs for weed mapping and spraying (UAV-IS) and to optimize UAV application parameters and assess the influence of nozzle type on the potential for off-target movement.

In the first study, field experiments were conducted to characterize the effect of 1, 3, 5, and 7 m s^{-1} application speeds using extended range flat spray, air induction flat spray, and turbo air induction flat spray nozzles on spray coverage and uniformity of UAV applications. Experiments measuring the drift potential of UAV applications using extended range flat spray, air induction flat spray, turbo air induction flat spray, and hollow cone nozzles under 0, 2.24, 4.47, 6.71, and 8.94 m s^{-1} perpendicular wind conditions in the immediate 1.75 m above the target were also conducted. The average coverage achieved at an application speed of 1 m s^{-1} was 45%, while an application speed of 7 m s^{-1} averaged 18% coverage. Coverage consistently

decreased as application speed increased across all nozzles. Off-target movement was observed under all perpendicular wind conditions across all nozzles but was non-detectable over 5 m from the target. Coverage from all nozzles exhibited a concave shaped curve in response to perpendicular wind speed due to turbulence. The highest achieved coverages in the drift studies were under both 0 and 8.94 m s^{-1} perpendicular wind conditions, but higher turbulence at the two highest perpendicular wind speeds (6.71 and 8.94 m s^{-1},) increased coverage variability while the lowest variability was observed at 2.24 m s^{-1}.

In the second study, glufosinate was applied at a rate of 594 g ai ha^{-1} in 151 L ha^{-1} and 187 L ha^{-1} for UAV and ground-based broadcast treatments in four experiments over two locations. Locations differed in weed population coverage, which affected application efficiency and efficacy. The UAV system was up to 200% more efficient at identifying and treating weedy areas, while minimizing treatment on non-weedy areas, than the broadcast application. The UAV system treated 20-60% less area per experimental unit than ground-based broadcast applications, but also missed up 26% of the weedy area, while broadcast applications covering almost the entire experimental unit only missed 2-3%. The benefit of the UAV-IS avoiding unnecessary application of non-weedy areas compensated for the small portion of weeds that were missed, while the advantage of the broadcast application of treating all weedy areas was minimized by the wasteful amount of herbicide that was applied to weed-free areas. Visual estimates of weed control showed UAV treatments were 12% and 25% higher than broadcast treatments at 14 and 28 DAT when treating highly aggregated weed populations, but 15% lower at both 14 and 28 DAT when treating higher populations with a more uniform distribution.

The rate of advancement has exceeded the rate of adoption and implementation of UAV technologies. At this point, UAVs offer the capability to complement existing, instead of replacing weed control technologies. Research generated in the present study will be used to further develop UAVs for agricultural operations and improve weed management strategies to maximize efficiency.

Integration of Unmanned Aerial Vehicles (UAVs) for Remote-Sensing and Spray Applications for Weed Management

by
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DEDICATION

This thesis is dedicated to the memory of my grandpa James “Pa” Jarman. Thank you for preparing me for everything and reminding me anything is possible. Without your life guidance and perpetual support, I would not have been capable of this accomplishment.

BIOGRAPHY

Joseph E. Hunter III was born and grew up in Kinston, North Carolina where he spawned a love for agriculture. While in high school he gained work experience on his grandfather's row crop farm. Upon graduating high school, he attended Lenoir Community College and obtained an associate degree in science before transferring to North Carolina State University in the fall of 2015 to pursue a Bachelor of Science. During the summer before moving to Raleigh, he worked on a temporary summer crew for Pioneer Hi-Bred International Inc. where he was first exposed to agricultural research. While pursuing his undergraduate, he spent a summer as a sales intern for Coastal AgroBusiness Inc., where he assisted sales personal with farm calls and learned valuable agronomic knowledge. He received his B.S. in agricultural science with minors in crop science and agricultural business management from North Carolina State University in the spring of 2017 and began working as a summer intern at Agricultural Systems Associates. He returned to North Carolina State University in the fall of 2017 to pursue a M.S. degree under the direction of Dr. Ramon Leon in the department of Crop and Soil Sciences. His research focused on utilizing and integrating unmanned aerial vehicles for weed management. Upon receiving his M.S. degree, he plans to return to Agricultural Systems Associates to conduct research as a research biologist.

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Literature Review

Weed Problems and Management

The Weed Science Society of America (WSSA) defines a weed as "any plant that is objectionable or interferes with the activities or welfare of man (Anonymous 2002)". Weeds compete against crops, reducing both crop yield and quality (Smith et al. 2009) resulting in significant economic damage (Moss 2019) and must be controlled for successful crop production (Gianessi 2013). The goal of weed management is to "optimize crop production and growers' profits through preventive tactics, scientific knowledge, management skills, and the use of weed control practices" (Buhler et al. 2000). Weed management must focus on the causes of weed problems and solutions based on integrating new techniques and knowledge (Buhler et al. 2000).

The standard practice to limit crop-weed competition has been to remove emerged weeds or prevent weed emergence (Smith et al. 2009). A wide array of challenges are associated with weed management practices, including selecting appropriate control tactics, timing of implementation, containing accumulating costs through the season, and minimizing seed production (Buhler et al. 2000). It is apparent no single weed management strategy can provide acceptable weed control on its own (Swanton and Weise 1991). Therefore, combining multiple weed control practices can be beneficial to ensure stable and consistent weed control over time.

Herbicides and tillage are the dominant and most effective forms of weed control across many production systems (Buhler et al. 2000). However, herbicides as chemical weed management are the main tool used for modern weed management (Harker and O'Donovan 2013; Heap 2014; Manalil et al. 2011; Metcalfe et al. 2018). Herbicides are highly effective weed control tools (Harker and O'Donovan 2013; Heap 2014) that are cost and time efficient (Heap 2014; Roush et al. 1990). The first chemical weed control began over a century ago with the introduction of inorganic copper salts to control emerged weeds (Hamill et al. 2004). 2,4-dichlorophenoxyacetic acid was developed in 1942 as the first selective herbicide (Oerke 2006), and more recently crops have been engineered to tolerate herbicides to which they are naturally susceptible. Genetically modified (GM) crops tolerant to herbicides were released in 1996 (Brookes 2014). These transgenic crops were tolerant to glyphosate, a non-selective herbicide used for broad spectrum emerged weed control, to be used during the growing season to control weeds without causing crop damage (Powles 2008). Since their initial release, GM crops have been rapidly adopted by farmers (Brookes 2014; Owen 2008). GM crops improved environmental benefits by decreasing the total amount of herbicide being used, allowing the adoption of soil conservation practices such as reduced- and no-tillage (Brookes 2014). The ease and convenience associated with GM crops and glyphosate had the unintended consequence of decreasing the diversification of weed management practices (Hamill et al. 2004; Powles 2008; Shaner and Beckie 2014) and has led to the usage of herbicides becoming the primary form of weed control (DeVore et al. 2012).

The use of herbicides as weed control is growing worldwide (Gianessi 2013), including in developing countries (Walsh et al. 2012), because they decrease the need for hand labor for weeding (Hamill et al. 2004; Oerke 2006) and improve the efficiency of mechanical harvest of crops (Oerke 2006). Worldwide industrialization has created hand labor shortages, driving chemical weed management adoption (Gianessi 2013). The worldwide adoption of herbicides for crop production has greatly influenced weed science research (Wyse 1992), centering it around herbicide efficacy and environmental fate (Davis et al. 2009).

Herbicides have greatly improved weed control and contributed significantly to increasing crop yields by enabling earlier planting dates, allowing for narrower row spacing, and decreasing the need for crop rotation (Buhler et al. 2000; Gianessi 2013; Hamill et al. 2004). The development of postemergence herbicides favored adoption of reduced-tillage systems (Buhler et al. 2000; Hamill et al. 2004; Somerville et al. 2017), where tillage had once been the primary form of weed control (DeVore et al. 2012). Cultivating crops for weed control requires more energy than applying herbicides (Gianessi 2013). Intensive tillage can lead to environmental issues such as soil erosion and pesticide run-off (DeVore et al. 2012). Due to these issues, tillage as a main weed control practice is considered an unsustainable practice and has decreased worldwide for weed control (Gianessi 2013). Reduced and no-till systems as alternative practices decreasing soil erosion and water pollution (Hamill et al. 2004) have been deemed more sustainable (DeVore et al. 2012).

Spray Applications and Drift

Spraying pesticides comprises the release of the chemical solution to the intended target, landing and retention of spray on the target, and its leaching, volatilization, and decay of spray residues (Combellack 1982). Proper spray coverage is very important for all spray applications, especially POST applied herbicides (Sharpe et al. 2017). The most challenging problem associated with spray applications for pesticide applicators and pesticide manufacturers is spray drift (Derksen et al. 1999). Spray drift is the movement of a pesticide through the air during or after the spray application to an unintended area outside the targeted zone (Carlsen et al. 2006; Derksen et al. 1999). Depending on the product being sprayed, the off-target movement of spray can damage non-target plants or contaminate surface water, air, or soil (Combellack 1982). The off-target movement of herbicides also creates a loss of herbicide from the intended target area, potentially leading to a reduction in weed control (Combellack 1982).

The extent of spray drift is influenced by a variety of meteorological factors including wind speed, atmospheric stability, turbulence, and temperature, and application factors such as sprayer type, nozzle type, nozzle size, nozzle pressure, application height, application speed, and nozzle angle (Carlsen et al. 2006). Properties of the spray formulation influenced by additives, density, and viscosity of the spray may also create an impact on spray drift (Carlsen et al. 2006). Wind speed is the most important meteorological factor for spray drift (Bode et al. 1976). Grover et al. (1997) documented consistent decreases in spray coverage over the target area as wind speed was increased. Furthermore, increases in application height and spray pressure both correlate with increases in spray drift (Frank and Ripley 1994). Bode et al. (1976) found application height to be the single most significant factor on spray drift, to which wind speed was second to. For these reasons, the accuracy and safety of any spraying equipment must be evaluated considering application height and wind conditions.

The physical properties of the spray solution are major contributors to spray drift (Miller and Butler Ellis 2000). The droplet spectra and droplet size are influenced by wind speed, boom height, spray pressure, and nozzle selection and in turn, contributes to spray drift (Combellack 1982). The spectra of droplet size distribution not only influence spray drift, but also spray deposition, coverage, and application efficacy (Bouse et al. 1990). The possibility of spray drift can be decreased by controlling the spray droplet spectra and droplet size (Legleiter and Johnson 2016). Preventing the formation of very small droplets (<100 µm in diameter) can allow for reductions in spray drift (Frank et al. 1991).

Different spray nozzles designs have been generated to modify the spray droplet’s spectra of size distribution and pattern (Combellack et al. 1996). Spray nozzles are capable of producing droplets ranging in size from 10- >1000 µm in size (Bouse et al. 1990). Some spray nozzles are designed to reduce drift when being compared to standard flat fan nozzles (Wolf 2005). Flat fan nozzles produce smaller droplets that are more prone to drift than air inducted drift nozzles (Legleiter and Johnson 2016). While smaller spray droplets increase the risk of spray drift, they can be desirable to improve herbicide efficacy by increasing the weed tissue covered with the spray solution (Knoche 1994). Standard flat fan nozzles are discouraged from being used by applicators under high wind conditions due to the potential of spray drift (Johnson et al. 2006). Anti-drift nozzles are designed to reduce the production of small, drift-prone spray droplets and replace them with much larger spray droplets (Derksen et al. 1999; Grover et al. 1997). The larger droplets are created by adding a pre-orifice to the nozzle tip before the nozzle orifice (Derksen et al. 1999). Adjuvants are also commonly added to the tank mix of spray solution to adjust the spray characteristics to exhibit desirable traits (Johnson et al. 2006). The additional costs of using drift controlling adjuvants makes them a more expensive option than the use of drift-reducing nozzles (Johnson et al. 2006). Adjuvants do not increase herbicide efficacy but can assist with preventing drift when paired with proper spray nozzles (Johnson et al. 2006).

Frank and Ripley (1994) compared spray applications from fixed winged airplanes, rotor driven helicopters, ground-based air-blast sprayers, ground-based high-pressure spray boom, and ground-based low-pressure spray boom, and concluded spray drift was consistent among all of them. Spray drift can be reduced by conducting spray applications under meteorological conditions characterized by low winds, low temperatures, low air turbulence, and high relative humidity (Carlsen et al. 2006; Goering and Butler 1975). Minimizing the spray application height and pressure also assist in combating spray drift (Carlsen et al. 2006; Goering and Butler 1975). Protective shields/hoods have been developed to cover sprayer booms to reduce the likelihood of spray drift (Wolf et al. 1993). These units have proven to be cumbersome, expensive, and difficult to use since the spray output cannot be observed through the shields (Wolf et al. 1993). Hooded sprayers also increase the variability in spray coverage beneath the hood and allows the spray to be susceptible to drift under high wind conditions (Wolf et al. 1993).

Precision Agriculture and Unmanned Aerial Vehicles

The concept of precision agriculture is not new. In fact, it is a very old technique still being conducted in its raw form today by subsistence farmers dividing their already small land partitions into even smaller units to grow and manage crops at an increased level of precision to maximize their yields (Oliver 2010). The modern version of precision agriculture can be defined as “a management strategy that uses information technologies to bring data from multiple sources to bear on decisions associated with crop production (National Research Council 1997).” Modern precision agriculture began during the 1980s to reduce fertilizer inputs and improve fertilizer allocation within fields (Oliver 2010; Zhang et al. 2002). Before then, the increase of mechanization had driven farm management to large scale uniform operations (Oliver 2010). Management units had become field size, increasing the amount of variability within them (Oliver 2010). Massey Ferguson released the first yield meter in 1982, providing real-time yield measurements that could be pinpointed in the field (Oliver 2010). Searcy et al. (1989) successfully created a grain yield map based on the flowrate data collected by the combine during harvest, exhibiting quantified in-field variability that could be linked to visually observed cultural problems including compacted soil and missing rows. Mulla (1997) found that soil phosphorus and grain yields were both spatially correlated with spatial patterns in soil organic matter content. Crop yield is a defining field variability indicator because it incorporates multiple spatial variables such as soil properties, topography, plant population, fertilization, irrigation, and pest infestations (Lee et al. 2010). Mulla (1993) split a wheat field into three separate fertility zones prescribing reduced rates compared to the conventional broadcast rate and found no significant differences in grain yield, but did observe differences in organic matter, soil moisture, residual nitrogen, and potential grain yield between fertility zones. Carr et al. (1991) correlated potential yield goals with soil types requiring different fertilizer rates and found consistent increases in profitability by applying fertilizer by soil type rather than field broadcast. Precision agriculture and can increase farm profitability through a more efficient management of farm inputs (Zhang et al. 2002) and also improves environmental quality (Mulla 1993). Precision agriculture provides the opportunity to change the distribution and timing of fertilizer and other agrochemical inputs based on spatial and temporal variability within field (Zhang et al. 2002). This lowers the risk and decreases the uncertainty associated with making management decisions (Schellberg et al. 2008).

The goals of aerial pesticide applications as an alternative to ground-based applications are to be cost-effective, efficient, and environmentally safe (Huang et al. 2017). Airplane based applications pose the highest risk for off-target spray drift among all agricultural spray equipment (Bird et al. 1992). Agricultural researchers and industry have developed new methods, technology, equipment, and spray formulations to minimize spray drift from aerial applications, including recommending a 3-meter application height (Fritz et al. 2011). Also, specific restrictions exist for allowable spray droplet size, because this is the main application variable for controlling off-target movement and optimizing coverage for pest control (Bird et al. 1992). Height of application and atmospheric conditions, including wind speed, are other factors affecting aerial spray drift that must be considered (Bird et al. 1992). Current pesticide labels generally prohibit aerial pesticide applications under very stable atmospheric and wind conditions to avoid air temperature inversions (Bird et al. 1992).

Unmanned aerial vehicles (UAVs) were developed for military use, but the rapid widespread of efficient technologies for batteries, global positioning systems (GPS), and computers accessible to civilians have increased the potential of UAVs for other purposes (Ehsani and Maja 2013; Hogan et al. 2017). The high versatility of UAV platforms makes them a viable alternative to manned aircraft for aerial pesticide applications (Wang et al. 2018; Xinyu et al. 2014; Ying et al. 2016). UAVs can conduct aerial applications at lower heights than manned aircraft and do not require a runway to take off or land (Xinyu et al. 2014). Their flight parameters make them suitable for areas of limited access for personal or conventional spray equipment (Wang et al. 2018). Per scale, UAVs consume less power than any alternative agricultural pesticide machinery (Ying et al. 2016). Physically removing the pilot from the aircraft lowers the safety risk associated with aerial pesticide applications (Wang et al. 2018). The light weight design and associated lower costs for UAVs over manned aerial spray equipment has further increased their potential for aerial applications (Xinyu et al. 2014).

China has been the lead developer of UAV technology for aerial pesticide applications due to their versatility benefits over manned aerial technology and fitment into Chinese agricultural systems (Yang et al. 2018). Xinyu et al. (2014) documented an increase canopy penetration due to the low flight parameters and downward propeller effect created from UAV flight parameters. As for manned aircraft, UAV application height, speed, and the interaction between these two parameters significantly affect spray uniformity and spray drift (Wang et al. 2017). The downwash produced for UAV rotors also affects spray droplets (Wang et al. 2018). The technology has outpaced proper regulation and the development of industry standards (Yang et al. 2018). Therefore, there is a need to properly characterize spray parameters for aerial pesticide application from UAVs, so regulators can and industry can develop the necessary recommendations to optimize effective pest control and minimize off-target movement (Wang et al. 2018, Yang et al. 2018).

The main limitation for UAV sprayers is battery and electric motor technology restraining the flight times and payload capacities of UAVs per flight, restricting their use and overall efficiency (Ying et al. 2016). Wang et al. (2017) tested four different commercially available UAV sprayers and found the daily working capacity of 13.4-18 ha^2 unsatisfactory for broadcast spray applications.

Precision agriculture is comprised of three main activities: data acquisition, data interpretation, and management response or action (Oliver 2010). Piloted aircraft and satellites have been primary platforms for obtaining remotely sensed imagery for data acquisition (Torres-Sanchez et al. 2013). Airborne imagery collected from aircraft and satellites allow for soil and vegetation pattern mapping of fields without the inconsistencies associated with data collected from harvest yield monitors or soil sampling (Dobermann et al. 2004). Managing spatial and temporal variability associated with agricultural production is the driving principle for precision agriculture (Basso et al. 2017). Even though precision agriculture technologies were originally intended to increase profits, the objectives have now changed to achieve sustainable profits while reducing environmental impacts (Dobermann et al. 2004). The agricultural industry has historically been a source of innovation, and the developing technologies associated with precision agriculture have the potential to shape the next large agricultural era (Basso et al. 2017).

Precision agriculture has a broad range of applications for agriculture management (Dobermann et al. 2004). The incorporation of agriculture sensors in precision agriculture allow for varying outputs, efficiency improvements, input cost reductions, reduced labor costs, improved worker safety, lower environmental impact, autonomous field navigation, crop monitoring, and pest monitoring (Lee et al. 2010). Rapid technology development through the 1990s significantly improved GPS guidance systems (Dobermann et al. 2004). The utilization of GPS for agricultural vehicle guidance has been a driving force for precision agriculture development, because it can increase the precision of different field practices (Dobermann et al. 2004). Chattha et al. (2014) successfully developed a tractor-based variable rate fertilizer spreader system with real time sensors to improve fertilizer allocation. Modern agricultural reflectance sensors can collect measurements of crops and weeds during the season without destroying them as was done with older methods (Felton et al. 2002). The accumulation of biomass is a proven direct measurement function of crop yield (Donald 1998), and numerous studies have successfully linked spatial variation to crop canopy reflectance, crop biomass, leaf area index, and crop yield (Dobermann et al. 2004). By using different vegetation traits that can be remotely and automatically measured with sensors, it is possible to implement corrective actions in space and time to maximize yield.

The same principles described above for precise management of the crop can be used to manage weeds. Spatial information can be applied to site-specific weed management to locate and target weed infestations in fields (Swinton 2005). Herbicide applications are conventionally applied as broadcast sprays, neglecting in-field weed distribution variation (Giles and Slaughter 1997; Hong et al. 2012; Peteinatos et al. 2014) and assuming the worst weed infestation (Tian 2002). The development of smart-spraying systems could visually detect weeds and conduct site-specific chemical spraying (Hong et al. 2012; Tian 2002) avoiding treating weed-free areas as currently done with broadcast applications. Smart-spraying systems are comprised of two separate steps: detection and application (Shaner and Beckie 2014). When separate, each step has the potential for errors. By combining the two separate systems, their errors may nullify one another or increase the potential for misapplications. A smart-spraying system using spatially accurate weed mapping will increase application efficiency and minimize environmental impact (Tian 2002).

Temporal variations in weed populations are as important as spatial variations for agricultural management (Dobermann et al. 2004), so weed detection and mapping must be done at the right time. However, ground-based sensors depend on adequate soil moisture conditions and the absence of barriers for movement across the field and landscape. Issues with obtaining adequate remotely sensed data are overcome with UAVs (Torres-Sanchez et al. 2013). UAVs offer a low-cost remote sensing platform capable of achieving desired spatial and temporal resolutions (Lopez-Granados 2011) even when conditions are limiting for ground-based sensors. UAVs with attached cameras are commercially available in the marketplace (Sugiura et al. 2016). The resolution of images collected with UAV based remote sensors is considerably higher than the one of images from satellites and airplanes (Singh and Frazier 2018). UAVs can remotely sense data at varying altitudes to achieve the desired spatial resolution (Torres-Sanchez et al. 2013; Lopez-Granados et al. 2016). Satellite data collection is frequently prevented by weather conditions that favor cloudiness (Peteinatos et al. 2014). Conversely, UAV data acquisition is very easy to conduct (Shaner and Beckie 2014) and can be done during cloudy days. UAVs also overcame remote sensing difficulties from manned aircraft associated with high cost, low resolution, and equipment size and weight (Ehsani and Maja 2013). The capabilities of

UAVs to obtain data over large areas in short amounts of time allows for more detailed planning for the design and implementation of the best management strategies compared with real-time ground-based sensors that depend on predetermined herbicide treatments (Rasmussen et al. 2013; Shaner and Beckie 2014).

Current UAV technology is comprised of a multitude of sensors, configurations, and obtainable data resolutions (Dobermann et al. 2004). The newest UAVs are capable of carrying multiple sensors at once (Maes and Steppe 2019), which can enable and simplify the simultaneous collection of multiple measurements (Singh and Frazier 2018). UAVs can be fitted with red, blue, and green (RBG), multispectral, hyperspectral, or thermal cameras (Ehsani and Maja 2013; Maes and Steppe 2019). Thermal cameras attached to UAVs have been used to detect drought stress (Maes and Steppe 2019). The use of hyperspectral cameras has been severely limited due to their high cost, while multispectral cameras have difficulty distinguishing weed seedlings (Lopez-Granados 2011). RBG cameras attached to UAVs can capture slightly finer resolution than multispectral cameras (Lopez-Granados et al. 2016) and have been used to phenotype crop differences (Sugiura et al. 2016).

Pest maps created from UAV imagery for agricultural pest management have only been developed for weeds (Lopez-Granados 2011; Lopez-Granados et al. 2016; Maes and Steppe 2019). UAV technology offers new potential for site-specific weed management (Maes and Steppe 2019). UAVs for remote sensing and aerial pesticide applications can be unified for integrated weed management to identify and treat weeds. The limitations of UAVs for broadcast pesticide applications do not severely limit their use for more efficient site-specific management. UAV sprayers create a new platform to manage weeds and combat herbicide resistance (HR) by reducing selection pressure by incorporating multiple mechanisms of action of different herbicides as tank mixes or alternating treatments while accounting for spatial weed population dynamics by using site-specific management strategies. UAV detection and mapping can also be used to identify weeds surviving herbicide applications due to resistance, and UAV sprayers can be directed to those survivors to control them with herbicides with different mechanisms of action before they produce seed. This will also help delay HR evolution and increase herbicide stewardship in a low-cost and efficient manner. Sensors still need to be optimized for UAV data acquisition for developing management practices (Singh and Frazier 2018). While data collection has improved, data processing for decision-making is still difficult (Dobermann et al. 2014; Shaner and Beckie 2014). Data processing and interpretation requires skills and knowledge to optimize decision-making (Hogan et al. 2017). To favor adoption, new UAV technologies must be user friendly and economically affordable (Primicerio et al. 2012).

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CHAPTER 1: Coverage and Drift Potential Associated with Nozzle and Speed Selection for Herbicide Applications using an Unmanned Aerial Sprayer

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In recent years, unmanned aerial vehicle (UAV) technology has expanded to include UAV sprayers capable of applying pesticides. Very little research has been conducted optimizing application parameters and measuring the potential of off-target movement from UAV-based pesticide applications. Field experiments were conducted in Raleigh, NC during the spring of 2018 to characterize the effect of 1, 3, 5, and 7 m s^{-1} application speeds (i.e. equivalent to 151, 50, 30, and 22 L ha^{-1}) and extended range flat spray, air induction flat spray, and turbo air induction flat spray nozzles on target area coverage and uniformity of UAV applications. Experiments measuring the drift potential of UAV applications using extended range flat spray, air induction flat spray, turbo air induction flat spray, and hollow cone nozzles under 0, 2.24, 4.47, 6.71, and 8.94 m s^{-1} perpendicular wind conditions in the immediate 1.75 m above the target were conducted outdoors in the absence of natural wind in Raleigh, NC. The highest coverage was achieved with an application speed of 1 m s^{-1} and ranged from 30 to 60%, while applications at 7 m s^{-1} yielded 13 to 22% coverage. Coverage consistently decreased as application speed increased across all nozzles, with extended range flat spray nozzles declining at a faster rate than air induction nozzles likely due to higher drift. Off-target movement was observed under all perpendicular wind conditions with all nozzles tested but was non-detectable beyond 5 m away from the target. Coverage from all nozzles exhibited a concave shaped curve in response to perpendicular wind speed due to turbulence. The maximum target coverage in the drift studies was observed when perpendicular wind was 0 and 8.94 m s^{-1}, but higher turbulence at the two highest perpendicular wind speeds (6.71 and 8.94 m s^{-1},) increased coverage variability while the lowest variability was observed with at 2.24 m s^{-1} wind. Results from all experiments suggested air induction flat spray and turbo air induction flat spray nozzles and an application speed of 3 m s^{-1} provided adequate coverage of target areas while minimizing the risk of off-target movement.

Introduction

For many years manned aircraft have been utilized in agriculture to collect aerial imagery or carry spraying systems over large areas in short periods of time (Huang et al. 2013). Aerial pesticide applications are used to prevent damage to crops in areas that are inaccessible for ground-based equipment (Bretthauer 2015). Piloted aircraft require large open areas for safe operation, leaving smaller fields to be sprayed with conventional ground equipment, which now can be managed using smaller unmanned aerial vehicles (Huang et al. 2013). An unmanned aerial vehicle (UAV) is an unpiloted, reusable, aerial vehicle that is controlled remotely, semi-autonomously or autonomously to perform specific tasks (Blyenburgh 1999). Aerial pesticide applications from manned aircraft are considered extremely dangerous due to their high frequency of accidents (Mannarino et al. 2017). The hazards along with the requirement of expensive equipment and personnel to conduct manned aerial applications makes them an expensive option. UAV aerial applications are considered a safer alternative to manned aircraft due to the lack of an on-board pilot (Faical et al. 2017; Giles 2016; He 2018).

Precision agriculture is a form of site-specific crop management based on observing, measuring, and responding to inter- and intra-field variability in cropping systems. UAVs have been developed in support of precision agriculture to carry out remote sensing and pesticide spraying missions (Huang et al. 2013). Unmanned aerial systems (UAS) can acquire the high temporal (e.g. daily acquisition) and high spatial (e.g. cm) resolutions that modern precision agriculture requires (Zhang and Kovacs 2012). These advantages, along with others such as ease of operation and nondestructive data acquisition, have driven research into integrating UAVs with a diversity of remote sensing technologies (Deng et al. 2018).

Precision agriculture offers an alternative for reducing and optimizing the use of potentially harmful chemicals by decreasing the use of broadcast applications common in conventional agriculture (Zhang and Kovacs 2012). POST herbicide applications using site-specific approaches have shown to be a viable alternative to reduce herbicide usage (Christensen et al. 2009; Gerhards and Oebel 2006; San Martín et al. 2016; Wiles 2009). Castaldi et al. (2017) reduced the amount of herbicide applied by 39% using a precision weed management system combining UAV-generated weed maps and a tractor-based spray system comprised of 12 independent boom sections capable of spraying independently. Huang et al. (2008) successfully developed an autonomous UAV spray system that could be integrated with remotely sensed data and concluded that UAVs have exceptional potential for precision weed management.

The first pesticide applying UAV was developed in Japan by Yamaha in 1985 (Xiongkui et al. 2017), but the exportation of Yamaha pesticide applying UAVs from Japan was banned in 2007 to protect the technology from competitors (Xue et al. 2016). In recent years, China has developed and implemented the use of UAVs for aerial applications for crop protection (Fengbo et al. 2017; He 2018; Lan et al. 2017; Meng et al. 2018; Xiongkui et al. 2017; Xue et al. 2016). He (2018) attributed UAV growth in China to shortages in agricultural labor and the technology’s versatility for applying pesticides in limited access areas such as rice paddies and hillsides.

While UAV spraying technology has seen advancements and implementation in Asia, North America and Europe have advanced at a much slower pace (Giles 2016). UAV missions associated with carrying and dispersing pesticides are considered more hazardous than remote sensing missions (Giles 2016). The Federal Aviation Administration (FAA) requires all commercial UAV pilots to comply with the Part 107 of the U.S. Federal Aviation

Administration, requiring an up to date federal license to conduct all missions other than for recreational purposes, and states might have stricter requirements. Giles et al. (2016) successfully applied pesticides to a California vineyard using an UAV sprayer and concluded UAV spray applications are feasible for spraying specialty crops. Due to the scarce experience with these new technologies, there is limited information about potential off-target movement associated with drift resulting from UAV aerial applications (Brown and Giles 2018).

UAV pesticide applications provide a lower spray volume than conventional aerial or ground-based applications, and an application height lower than aerial, but higher than ground-based applications (He 2018). This method creates a wide array of associated parameters (e.g. spray volume, nozzle selection, wind conditions, application speed) to be determined as well as optimized. Furthermore, spray capable UAVs can differ significantly among manufacturers. During China's rapid development of UAV pesticide technology, more than 200 manufacturers have created over 169 different types of UAVs (Xiongkui et al. 2017). Optimization of spray patterns based on spray system configurations have yet to be achieved (He 2018). Lan et al. (2017) compared five aerial pesticide applying UAVs from the literature and found differences among their optimal operating parameters and needed buffers for application. Similarly, Yongjun et al. (2017) found different optimal operating parameters for UAV applications over different growth stages of corn. Despite previous studies, the accuracy and uniformity of UAV pesticide applications have not been evaluated under different flight configurations and conditions (Faical et al. 2017).

The lack of research pertaining to UAV spraying has limited the development of standards to determine recommended guidelines for the effective and safe use of this technology (He 2018). Wind variability and nozzle selection have been documented as two influential parameters on achievable coverage and off-target movement of aerial applications (Hewitt et al. 2009). Bode et al. (1976) found wind speed to be the most important meteorological factor on spray applications, where spray coverage decreases as wind speed increases (Grover et al. 1997). The spray droplet's spectra of size distribution and pattern can be altered by different spray nozzle designs (Combellack et al. 1996). Spray drift, deposition, coverage, and efficacy are influenced by the spectra of droplet size (Bouse et al. 1990). Smaller sized droplets can increase spray coverage, improving herbicide efficacy, but also increase the risk of spray drift (Knoche 1994). Air inducted drift nozzles produce large droplets that combat spray drift better than the small droplets produced by flat fan nozzles (Legleiter and Johnson 2016). Therefore, the objectives of the present study were (1) to determine how flying speed and nozzle type affect target coverage; and (2) to determine the potential off-target movement risk under varying perpendicular wind conditions for pesticide applications using a UAV sprayer.

Materials and Methods

Flight speed experiments were conducted at the Lake Wheeler Turfgrass Field Laboratory, Raleigh, NC (35.74 N, 78.68 W). The experimental area was an open sod field, and applications were made during March and April of 2018 when wind speeds were 1.34 to 3.58 m s^{-1}. Additionally, another set of outdoor experiments on the influence of perpendicular wind conditions and nozzle type on drift risk were evaluated at the North Carolina State University Weed Control Laboratories in Raleigh, NC (35.79 N, 78.69 W). These studies were conducted during days with low to no wind in August 2018 in a low elevation area surrounded by tree windbreakers and tall walls, that protected the experimental area from wind.

Application Speed and Nozzle Type

The study was conducted as a factorial arrangement of four application speeds and three spray nozzle types, for a total of 12 treatments, in a completely randomized design with 4 replications, and the study was repeated. Applications were made with a DJI AGRAS MG-1 octocopter sprayer (DJI, Shenzhen, China) at a flying altitude of 3 m over the target area. This height was the minimum allowed by the autonomous flying specifications for this drone sprayer. For an autonomous application, the pilot is required to set A and B waypoints (i.e., start and end of application path, respectively). The experimental units were centered on the flight path. The A and B points were located 3 m before and after the sampling area, respectively in each experimental unit. This was done to achieve the desired speed and spray coverage over the target area. Autonomous application speeds were 1, 3, 5, and 7 m s^{-1}, and were selected based on the settings for the UAV sprayer. Flow rate remained constant at 680 ml min^{-1} per nozzle for all applications with 4 nozzles covering a 3 m swath, creating an inverse relationship between application speeds and application volumes of 151, 50, 30, and 22 L ha^{-1}. Extended range flat spray nozzles (TeeJet®, XR11002VS, Spraying Systems Co., Wheaton, IL), air induction flat spray nozzles (TeeJet®, AIXR 11002VP, Spraying Systems Co., Wheaton, IL), and turbo air induction flat spray nozzles (TeeJet®, TTI 11002VP, Spraying Systems Co., Wheaton, IL) were tested. These nozzles were selected because of their fine, coarse, and ultra-course droplet size profiles, respectively. Experimental units were 30 m^2 (10 m by 3 m), and a sampling area of 2.3 m^2 (3 m by 0.76 m) was located in the plot center and covered with brown kraft paper (DIY Crew, Seattle, WA). Paper was secured to the ground with rebar and binder clips placed along the edges to maintain a uniform and smooth surface during the application. A solution of Lazer blue concentrated spray pattern indicator (20 ml L^{-1}, Sanco Industries, Inc., 1819 S. Calhoun St., Fort Worth, IN) was used to make visible the droplet distribution pattern on the sampling area.

A 0.25 m^2 (0.5 m by 0.5 m) frame was used for image collection to evaluate application coverage over the paper from one sampling point. Paper samples were photographed with a Canon EOS Rebel T6 EF-S 18-55 mm (Canon U.S.A., Inc., Melville, NY) immediately after each experimental run. Images were cropped to the inside edge of the frame for image analysis. Image analysis was conducted by supervised classifications using ArcMap 10.5.1 (Esri, Redlands, CA). Image samples were individually subjected to an interactive supervised classification and divided into three classes; sprayed, missed, and undetermined. Classified image files were then transformed to polygon files to create pixel counts for each class. Undetermined pixel counts represented less than 0.02% of each classified image sample. Coverage was determined based on the number of sprayed pixels divided by the sum of sprayed and non-sprayed pixels. Statistical analyses were conducted using the GLIMMIX and REG procedures in SAS (9.2 SAS® Institute Inc. Cary, NC 27513) with α=0.05.

Perpendicular Wind Conditions and Nozzle Type

The experiment was conducted as a factorial arrangement of five simulated perpendicular wind speeds and four spray nozzle types, for a total of 20 treatments, in a completely randomized design with 3 replications, and the experiment was repeated. Perpendicular wind speeds were 0, 2.24, 4.47, 6.71, and 8.94 m s^{-1}. Wind was simulated using a 61 cm Hi-Vol/Hi-Velocity industrial fan (Model 5M170, Dayton Electric Manufacturing Co., Niles, IL) set at different distances from the application target at the center height of 1 m to simulate varying wind conditions. This setting created a constant perpendicular wind from 0.25 m to 1.75 m height over the target area, and the area of influence was 1.5 m wide. Extended range flat spray (XR) nozzles, air induction flat spray (AIXR) nozzles, turbo air induction flat spray (TTI) nozzles, and hollow cone spray (HC) nozzles (TeeJet®, TXR8002VK, Spraying Systems Co., Wheaton, IL 60187.) were tested. Single 5.08 cm by 7.62 cm water-sensitive spray cards (TeeJet®, Spraying Systems Co., Wheaton, IL) were placed horizontally on the ground at 2.5, 5, 7.5, 10, and 15 m from the application target. Three spray cards were set at 0 m from the target along the flight path of the UAV sprayer and were spaced at 50 cm from one another. Spray cards were held in place by binder clips attached to plywood bases. A UAV sprayer (DJI AGRAS MG-1 octocopter) carrying water was flown at an autonomous application speed of 3 m s^{-1} (50 L ha^{-1}) and a height of 3 m for all experimental runs. This flying speed was selected based on the previous study to maximize target coverage and reduce drift due to flying speed. The UAV sprayer flight path started 5 m before the target area and finished 5 m after.

Water-sensitive spray cards were collected immediately after each application, and digital images were recorded and processed using the unsupervised classification in ArcMap 10.5.1 and creating four classes; dark blue, light blue, dark yellow, and light yellow. Classified images were subjected to the methodology previously outlined, with coverage being determined by the sum of the blue pixels being divided by the sum of all pixels per spray card. All statistical analyses were conducted using the GLIMMIX procedure in SAS (9.2 SAS® Institute Inc. Cary, NC 27513) with α=0.05. The only significant two factor interaction was between distance from the target and wind speed, allowing for analysis by nozzle type.

Results and Discussion

No significant experimental run by treatment interactions were detected ($P>0.05$), so the results for all experiments were analyzed and are presented pooled across both runs.

Application Speed and Nozzle Type

Coverage decreased as application speed increased regardless of nozzle type, although within each application speed, nozzle type determined coverage (Figure 1). At the minimum speed of 1 m s^{-1}, coverage ranged from >60% for XR nozzles to 31% for TTI nozzles, while at the maximum speed (7 m s^{-1}) coverage decreased to approximately 22% for AIXR nozzles, 16% for XR, and 13% for TTI nozzles. Coverage observed in the present study was higher than in previous nozzle research. Nansen et al. (2015) reported coverage <40% at application volumes of 100-140 L ha^{-1}, and no more than 10% coverage with 30-40 L ha^{-1} for both XR and AIXR nozzles. In the present study, UAV sprayer applications provided 31-61% coverage at 151 L ha^{-1} and 13-22% at 22 L ha^{-1}. Teske et al. (2018) found that rotor downwash can assist directing spray material towards the ground when operating beneath a critical application speed. Downward force from the UAV's propellers helped force spray solution towards the target, improving coverage.

The volume applied per unit of time stayed constant for all application speeds, so it was expected that coverage would decrease as speed increased due to lower application volume per area unit. However, the rate of decrease in coverage as speed increased was disproportionally higher for XR nozzles when compared with AIXR and TTI nozzles. As application speed increased, coverage created from XR nozzles decreased more rapidly than from AIXR and TTI nozzles. This more rapid decrease in coverage of XR nozzles may have been the result of increased off-target movement of driftable droplets resulting from the faster flight speed. XR nozzles produce smaller spray droplets than AIXR and TTI nozzles (Creech et al. 2015). Smaller droplets have been shown to be more susceptible to drift than larger droplets during conventional aerial applications (Bird et al. 1996).

Perpendicular Wind Conditions and Nozzle Type

TTI nozzles consistently produced the lowest coverage among the nozzles tested (Figure 2). These results were similar to those found in the application speed and nozzle selection experiment. Coverage produced by TTI nozzles did not exceed 15%, while other nozzles achieved closer to 20% coverage at the target area with no perpendicular wind.

Drift was detected under all perpendicular wind conditions for all nozzles up to 5 m downwind from the target. At 5 m downwind from the target, coverage was highest under 4.47 and 6.71 m s^{-1} perpendicular wind conditions (Figure 2 and 3). At distances of 7.5 m and greater, coverage created from driftable droplets was close to zero and did not differ among nozzles (Figure 2). It is worth noting that the position of the fan creating the perpendicular wind from 0.25 m to 1.75 m above the target area creates a limitation on measuring the actual drift potential of a UAV sprayer. Air currents and windy conditions can be present at any height above the ground. It is likely a wind current at higher heights than the one studied here could carry driftable spray particles farther than wind currents at lower application heights such as the one tested. Therefore, the results of the present study are more informative of nozzle type differences than drift distance (Figure 2).

Although we expected a consistent decline in coverage over the target area as perpendicular wind speed increased, coverage exhibited a concave shape curve in response to this factor (Figure 2). Thus, the lowest target coverage was achieved at the intermediate perpendicular wind speed (4.47 m s^{-1}), and the extreme speeds (0 and 8.9 m s^{-1}) exhibited coverage that was almost twice greater than the former. Droplets sprayed from an UAV are subject to both vertical and horizontal forces once released (Yang et al. 2018). Therefore, it might be necessary to identify critical application speeds for UAV sprayers where the downwash from the rotors does not become outwash before reaching the target (Teske et al. 2018). Otherwise, the interaction between speeds greater than the critical speed and perpendicular wind conditions may increase the likelihood of off-target movement (Teske et al. 2018). The result of contrasting wind directions and forces lead to observed turbulence, where the droplets could be either forced downward towards the target or recirculated upwards under high wind conditions in lower layers. All nozzles subjected to perpendicular wind speeds greater than 4.47 m s^{-1}, had observable turbulence and recirculation of droplets above the target area, which contributed to a higher coverage, albeit more variable, than under moderate wind conditions.

Total coverage alone must not be the only consideration to determine the optimum parameters for UAV applications; uniformity of spray coverage must be considered too. Coverage at the target area varied between wind speeds across all nozzles (Figure 4). Coverage variability was greatest under perpendicular wind speeds ≥4.47 m s^{-1}, and lowest at 2.24 m s^{-1} (Figure 4).

Off-target movement of spray droplets is favored by the stability of atmospheric conditions and wind speed. In fact, current pesticide labels for aerial applications usually prohibit spraying during very stable atmospheric conditions (Bird et al. 1996). Extremely stable conditions are characterized by a light breeze or calmness. Higher wind speeds have a neutralizing effect on atmospheric stability and higher winds can lessen the effects of extremely stable conditions (Bird et al. 1996).

Results from the present study indicate that AIXR nozzles at an application speed of 3 m s^{-1} provided the best coverage of nozzles tested while reducing the risk of off-target movement. HC and XR nozzles were more prone to drift than AIXR nozzles, and TTI nozzles provided the lowest coverage. While acceptable coverage can be achieved under extreme perpendicular wind conditions due to turbulence, the potential for off-target movement may represent a serious threat for application efficiency and safety. Future research should continue optimization of application parameters, including application height. Pesticide formulation and adjuvants can have significant impacts on coverage for pesticide applications and should be investigated for UAV-based aerial sprays. Evaluations of larger scaled application areas are needed to fully understand the potential and limitations of this technology.

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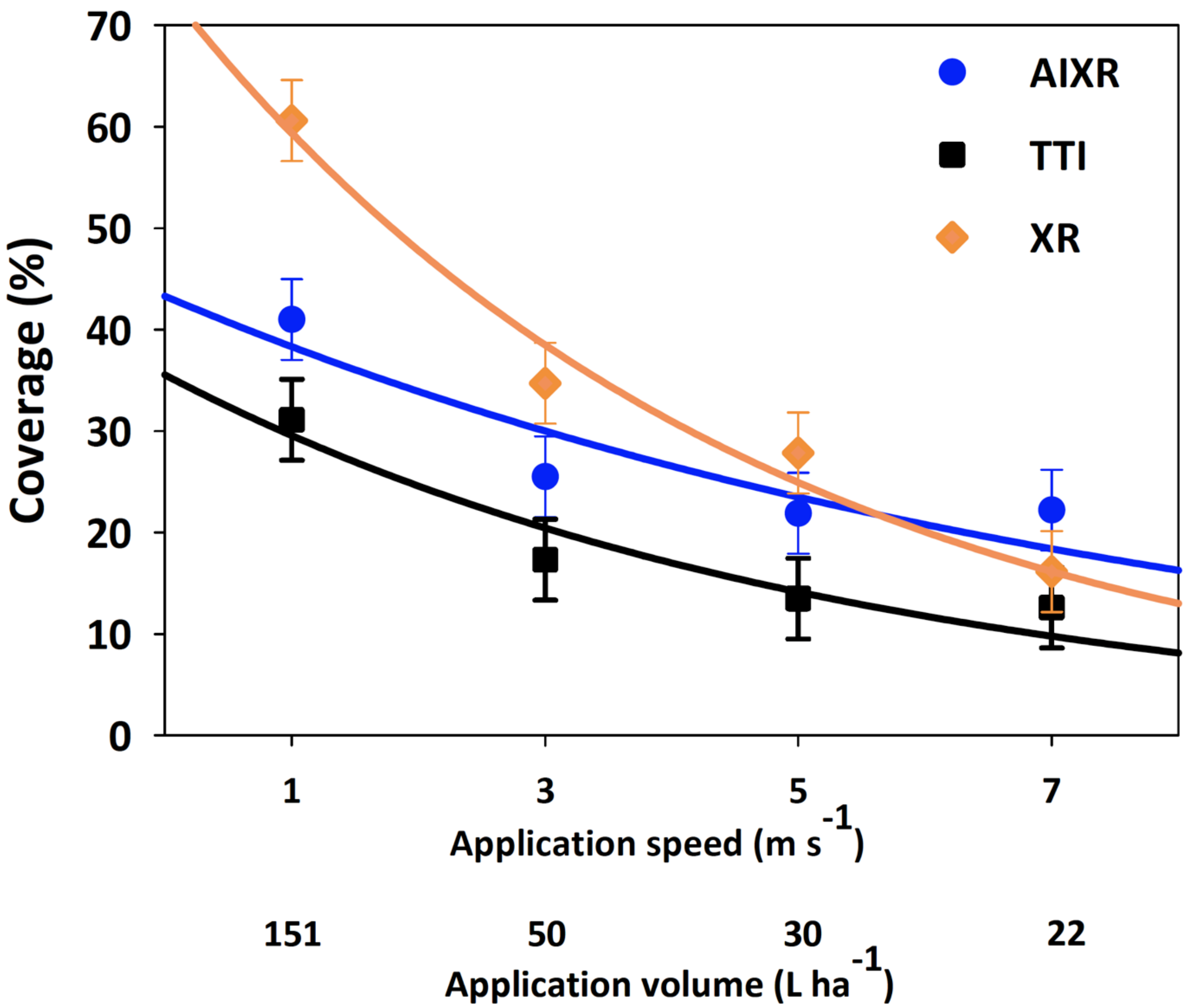

Figure 1. Target area coverage resulting from UAV applications with fine (XR), coarse (AIXR), and ultra-coarse (TTI) nozzles at increasing application speeds at a fixed application output per time unit (680 mL min^{-1} per nozzle and a total of 4 nozzles covering a 3 m swath). Application speeds of 1, 3, 5, and 7 m s^{-1} were equivalent to application volumes of 151, 50, 30, and 22 L ha^{-1}, respectively. Values are averaged over repeated study and 4 replications for each. Error bars represent 95% CI.

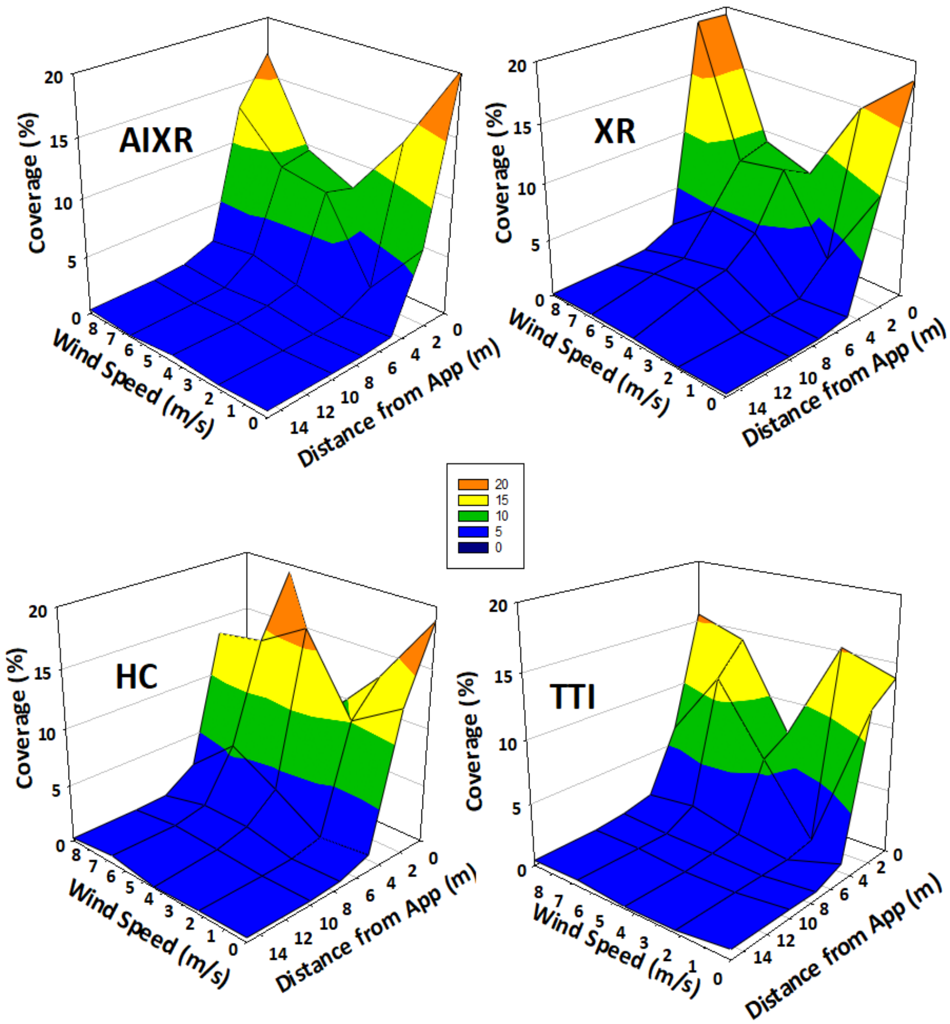

Figure 2. Spray coverage for AIXR, XR, HC and TTI nozzles influenced by perpendicular wind speed at different distances downwind from the target area. X axis represents distance downwind from target area (m), Y axis represents perpendicular wind speed (m s^{-1}) over target area, and Z axis represents coverage (%). Values are averages of two experimental runs with 3 replications per run.

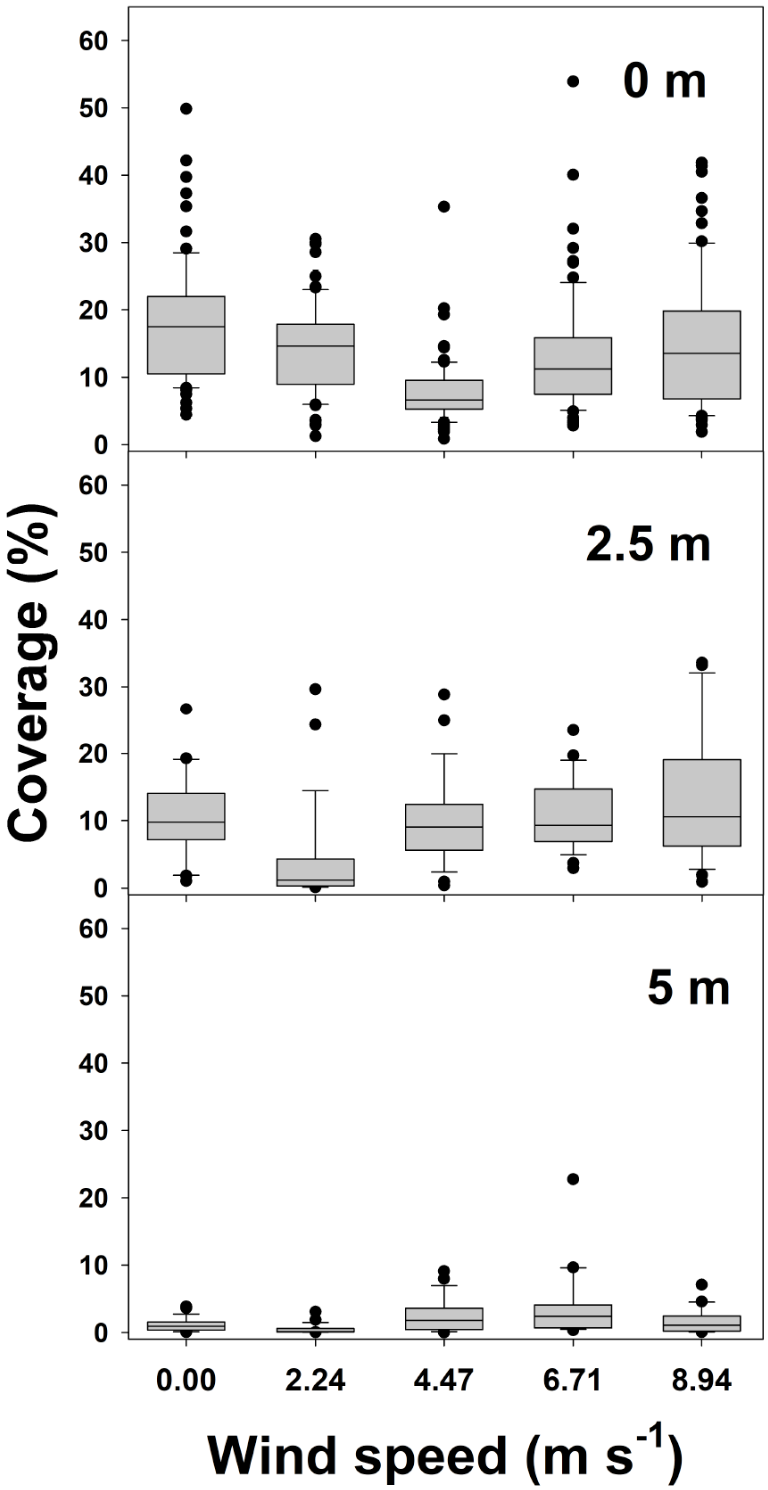

Figure 3. Box plots comparing spray coverage at 0, 2.5, and 5 m from the target area depending on perpendicular wind speed (m s^{-1}). Values are combined over four nozzle types, and two experimental runs with 3 replications. Error bars represent 5th and 95th percentiles.

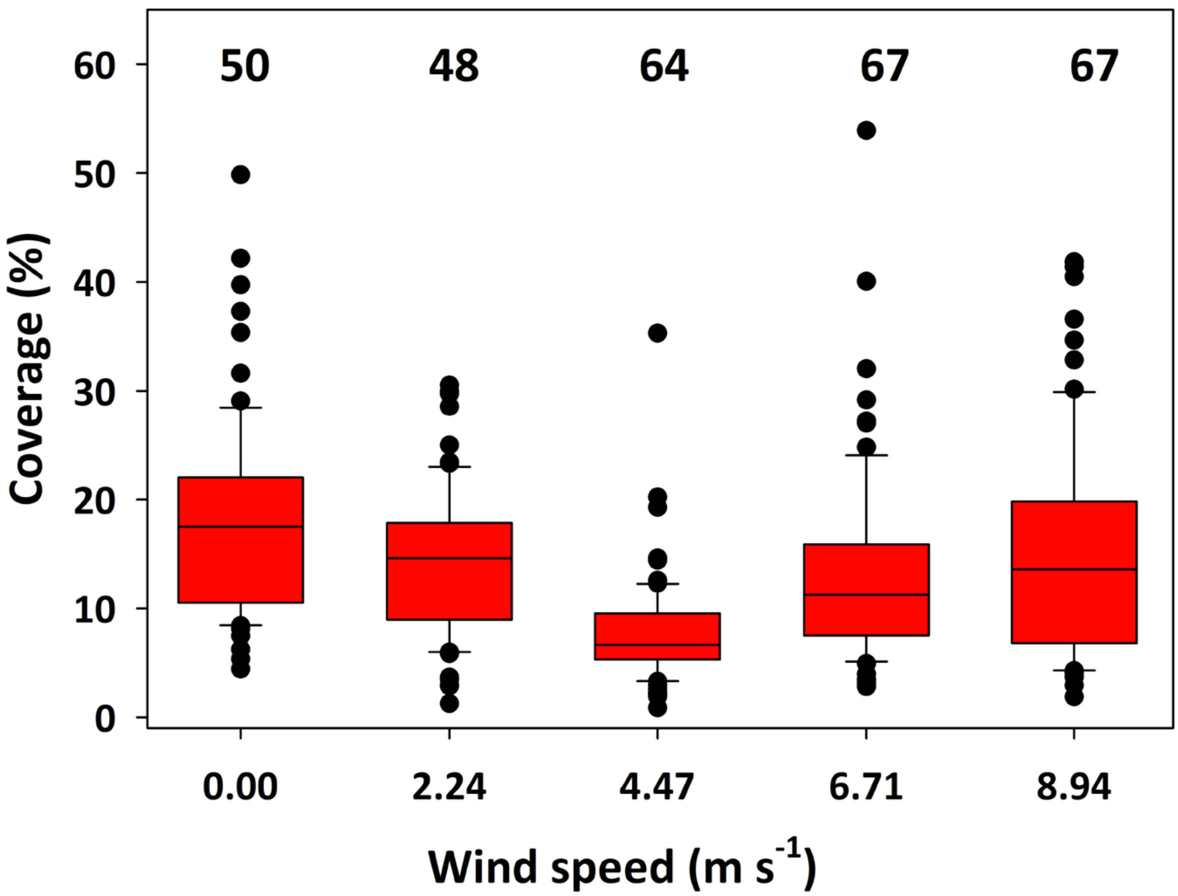

Figure 4. Influence of perpendicular wind speed (m s^{-1}) on spray coverage on target area. Values are pooled over four nozzle types, and two experimental runs with 3 replications each. Error bars represent 5^{th} and 95^{th} percentiles. Values above each perpendicular wind speed box represent the coefficient of variation (%).

CHAPTER 2: Integration of Remote-Weed Mapping and an Autonomous Spraying Unmanned Aerial Vehicle for Site-Specific Weed Management

Article to be submitted for publication to Weed Science

Unmanned aerial vehicles (UAVs) have been used in agriculture to collect imagery for monitoring and decision-making purposes. Spray-capable UAVs are now commercially available worldwide for agricultural applications. Integrating UAV imagery and spraying technologies can offer a new alternative to implement site-specific weed management. Field studies were conducted to compare integrated UAV site-specific (UAV-IS) spray applications and conventional broadcast spray strategies. The non-selective herbicide glufosinate was used to visualize target and off-target vegetation that was treated. Experimental fields were characterized for weed population coverage, and the application systems were compared for application efficiency and efficacy. The UAV-IS was up to 200% more efficient at identifying and treating target weedy areas, while minimizing treatment on non-weedy areas, than the ground-based broadcast application. The UAV system treated 20-60% less area per experimental unit than ground-based broadcast applications, but also missed up to 26% of the weedy area, while broadcast applications covering almost the entire experimental unit only missed 2-3%. The efficiency of UAV management practices increased as weed spatial distribution was more aggregated (i.e., patchy). The benefit of the UAV-IS is to avoid applying non-weedy areas, but this benefit can be offset by allowing survival, growth and repdoruction of small portions of weeds that are missed due to errors in detection and application. Conversely, the advantage of the broadcast application of treating all weedy areas is minimized by the wasteful amount of herbicide that is applied to weed-free areas. Weed control based on injury was 12% and 25% higher with UAV-IS than broadcast treatments at 14 and 28 DAT when treating highly aggregated weed populations, but 15% lower at both 14 and 28 DAT when treating larger

populations with a more uniform distribution due to a higher proportion of missed weedy areas. Integrating UAV imagery for weed mapping and UAV sprayers can provide a new strategy for integrated weed management programs to improve efficiency and efficacy while reducing the amount of herbicide being applied.

Introduction

Precision agriculture is the concept of managing crop fields considering spatial variation and local field needs (Huang et al. 2013). Precision agriculture comprises four components; data collection, field variability mapping, decision-making, and management practice implementation (Zhang and Kovacs 2012). The increased adoption of precision agriculture has influenced the development of unmanned aerial vehicles (UAV) due to the abilities to conduct low altitude operations in small fields (Huang et al. 2013). Blyenburgh (1999) defines an UAV as an unpiloted, reusable, aerial vehicle that is controlled remotely, semi-autonomously, or autonomously to perform specific tasks related to the fulfillment of their mission. UAVs have proven to be capable of acquiring remotely sensed data at a higher spatial (cm) and temporal (daily) resolution than satellites (Huang et al. 2018; Zhang and Kovacs 2012). UAV technology offers a desirable platform for precision agriculture data collection that is highly flexible and easy to operate while collecting high spatial resolution data in a timely manner. Huang et al. (2018) suggested UAVs offer an advantageous platform over ground-based, satellite-based, or manned aircraft based remotely sensed data for detection of weeds from the crops due to their spatial and temporal resolution capabilities. UAVs have also proven to be cost-effective in obtaining a variety of accurate imagery for precision mapping (Perz and Wronowski 2018).

UAV spray technology, which has fallen behind remote sensing technology in the U.S., has seen a wider development in Asia (Giles 2016). Aerial applications prevent damage to the crop from spray equipment and allow timely pesticide applications following adverse weather conditions that may leave fields inaccessible to ground-based equipment (Bretthauer 2015). UAVs also create new management possibilities for agricultural systems that are too small for piloted aircraft to operate (Huang et al. 2013). Faical et al. (2017), Giles (2016), and He (2018) considered UAV aerial applications a safer alternative to manned aircraft since the pilot is not in immediate danger.

In recent years, China has developed and implemented UAVs for aerial applications of crop protection chemicals (Fengbo et al. 2017; He 2018; Lan et al. 2017; Meng et al. 2018; Xiongkui et al. 2017; Xue et al. 2016). UAV sprayers are capable of treating the small agricultural areas over complex geographic terrain not easily accessible to personnel or ground-based machinery (Xiongkui et al. 2017). Commercial UAV pesticide applications have become available in the U.S. even though a literature gap concerning the risks associated with the technology presently exists (Brown and Giles 2018).

UAV sprayers also hold potential for highly accurate site-specific treatments over larger areas. For example, Huang et al. (2008) successfully developed an UAV spray system capable of completing autonomous spot sprays. Furthermore, Castaldi et al. (2017) used UAV-generated weed maps and a variable-rate tractor-based spray system to achieve herbicide savings of 39% over conventional broadcast applications.

Huang et al. (2018) describes the next step for agricultural UAVs to be used as an integrated system (UAV-IS), using two separate UAVs with distinct missions of remote sensing and precision spraying or as a single unit for real-time operation. While UAVs have been proven capable of creating weed maps for site-specific weed management and for pesticide applications, the concept of conducting site-specific weed management with a UAV-IS has not been investigated. The present study utilizes an UAV-IS consisting of two separate UAVs for remote sensing and site-specific spraying. The main objective of the present study was to quantify the application efficiency and efficacy of an UAV-IS compared with a conventional ground-based broadcast spray.

Materials and Methods

Field experiments were conducted on two irrigated sod fields in Eagle Springs, NC (35.31 N, 79.71W) in a Candor sand (sandy, kaolinitic, thermic Grossarenic Kandiudult) soil with 0.75% organic matter, and on two non-irrigated sod fields in Willow Springs, NC (35.57 N, 78.66 W). In this last location, the soil was a Gritney sandy loam (fine, mixed, semiactive, thermic Aquic Hapludult) soil with 1.25% organic matter for one field and a mosaic of Gritney sandy loam and Wedowee sandy loam (fine, kaolinitic, thermic Typic Kanhapludult) with 1.8% organic matter for the other.

The studies were set up as randomized complete block designs with four replications and were repeated in space in two separate sod fields for each location during the summer of 2018. The treatments were UAV-IS site-specific herbicide application, ground-based broadcast herbicide application (i.e., standard conventional practice), and a non-treated control. A DJI AGRAS MG-1 octocopter (DJI, Shenzhen, China) was flown at 1 m s^{-1} at a height of 3 m (lowest flight height in autonomous mode recommended by the manufacturer) for UAV-based herbicide applications delivering 151 L ha^{-1}. Broadcast applications were done with a CO_2 backpack sprayer delivering 187 L ha^{-1} at a height of 0.5 m. Application volume selection was based on the maximum volume allowed by the UAV sprayer and the typical recommended volume for broadcast herbicide applications, respectively.

To detect and map weedy patches, images were collected at an altitude of 30 m using a DJI Phantom 4 Pro quadcopter (DJI, Shenzhen, China) and the mission planning application Pix4D Capture (Pix4D S.A., Lausanne, Switzerland) ran on an iPad mini 4 (Apple, Cupertino, CA). Collected imagery was stitched together to generate an orthographic image exhibiting a spatial resolution of 0.82 cm per pixel for the entire experimental field using Agisoft PhotoScan

1.4.4 (Agisoft, LLC, St. Petersburg, Russia). Ground landmarks were used for coordinate confirmation.

Natural Weed Population

The experiment was conducted at the Willow Springs, NC location in an out of production sod field of mixed grasses with a relatively high weed infestation predominantly comprised of common lespedeza (*Kummerowia striata* (Thunb.) Schindl.). Experimental units (10 m by 10 m) were identified arbitrarily from the constructed field map using ArcMap 10.5.1 (Esri, Redlands, CA) to include areas that had patches of common lespedeza (Figure 1a). There was a buffer area of at least 10 m between experimental units to avoid any issues related to possible off-target movement. Geospatial data constructed in the orthographic image provided coordinates for the vertexes of each experimental unit. A Montana® 680t GPS (Garmin International, Inc., Olathe, KS) was used to locate experimental unit vertexes in the field. Image collection was repeated to map weed patches within the experimental units (i.e., target area). Each experimental unit was subjected to supervised classification techniques and areas were consolidated into two classes: weeds present and weeds absent (Figure 1b). Flight paths for UAV-based site-specific treatments were created based on weed density and location within experimental units and coordinates were annotated to guide the UAV application (Figure 1c). Flight paths were determined based on the following criteria: i) no more than three individual flight passes per experimental unit were allowed, and ii) only weed patches larger than 1 m in diameter and with over 35% weed coverage were targeted since smaller less dense patches would require a broadcast treatment. These criteria were used to optimize herbicide use. More flight passes or targeting smaller or less dense weed patches would have created almost a broadcast application, defying site-specific weed management. Glufosinate (Liberty®, 280.39 g ae L^{-1}, BASF Corporation, Research Triangle Park, NC) was applied at a rate of 594 g ae ha^{-1} for site-specific and broadcast applications. Since glufosinate is a non-selective herbicide, its activity would be visual on the target and non-target areas. Image collection was repeated 14 days after the treatment (DAT) to map and quantify herbicide injury in the experimental area (Figure 1e). Visual ratings of the experimental units were collected using an UAV at 14 and 28 DAT.

Surrogate Weed Population

This study was conducted in Eagle Springs, NC in a sod field that had perennial tall fescue (*Festuca arundinacea* Shreb.) and no emerged weeds. Plots were arranged parallel to one another in both trials with an average plot size of 136 m^2 and 10 m buffers between plots to avoid drift issues. Potted tobacco plants (*Nicotiana tabacum* L. 'NC-196') 15 cm tall with 3-4 leaves were placed on the sod within each plot to simulate weed patches with different densities (3 to 15 plants m^{-2}) and shapes (quadrilateral, circle, triangle, and straight line), which were randomly assigned to each experimental unit. This variation in density and shape was included to create more challenging weed detection and spray situations.

Images were collected at an altitude of 30 m and processed as previously described to generate an orthographic image of the entire experimental area. Weed patches were identified visually from the orthographic map. Geospatial data attached to collected imagery provided locality and extent of weed pressure for site-specific applications. Flight maps for the UAV applications were designed to maximize efficiency by focusing on treating the target species and minimizing the treatment of non-target species. All individual weed patches were targeted due to the high spatial aggregation of the target species. A maximum limit of three flight paths were set per experimental unit. GPS coordinates for weed patches were obtained from the aerial field maps and used for UAV applications. Glufosinate was applied at a rate of 594 g ae ha^{-1} in 151 L ha^{-1} from 3 m for site-specific and 187 L ha^{-1} from 0.5 m for broadcast applications.

UAV image collection was repeated at 7, 14, and 28 DAT to map and quantify herbicide injury on the tall fescue. Tobacco plants were removed from the site after application once the herbicide on the leaves had dried and were maintained under greenhouse conditions. Tobacco plants were visually rated based on chlorosis, necrosis, and stunting (0 = no injury and 100 = plant death) for herbicide injury at 14 and 28 DAT. Shoot biomass of each individual plant was harvested 28 DAT and dried at 63 C for 4 days before plant dry weights were recorded.

Data Analysis

Post-treatment field maps were uploaded to ArcMap and georeferenced to pre-application data to be analyzed (Figure 1d). Injury distribution and intensity were visually verified on the ground and mapped on the orthographic image (Figure 1e). Maps with experimental unit perimeters, weed targets, and injured area were overlaid for data analysis (Figure 1f). Spatial data for each experimental unit was classified into four classes based on the presence of weeds (i.e. target area) and whether or not it was affected by the herbicide. The four classes were no weeds and no spray (true negative), weedy and no spray (false negative), no weeds and spray (false positive), and weedy and spray (true positive). The total area within each category was added per experimental unit and used to estimate several indexes (Sokolova and Lapalme 2009). Thus, application precision was determined per experimental unit as:

$$Precision = \left(\frac{Weeds\ treated}{Area\ treated}\right) = \left(\frac{True\ positive}{True\ positive + False\ positive}\right)$$

Eq. 1

Application recall was determined as:

$$Recall = \left(\frac{Weeds\ treated}{Weed\ infestation}\right) = \left(\frac{True\ positive}{True\ positive + False\ negative}\right)$$

Eq. 2

The Fscore allows for balancing the application's ability to hit the target with the minimum amount of herbicide required, and is estimated by combining the precision and recall to represent a resolution of application tradeoffs as follows:

$$F_{score} = \left(\frac{2 \times Precision \times Recall}{Precision + Recall}\right) \qquad \text{Eq. 3}$$

Additionally, a spray ratio was estimated as the total area sprayed per plot (inside and outside the plot [i.e., drift]) divided by the total area of the plot. This ratio was used to assess the overall application efficiency as follows

$$Application\ efficiency = \left[\frac{F_{score}}{\left(\frac{Total\ sprayed\ area}{Total\ plot\ area}\right)}\right] \qquad \text{Eq. 4}$$

The aforementioned parameters, weed control, visual ratings, and dry weight were analyzed using the GLIMMIX procedure and Tukey's honestly significant difference test for means separation in SAS (9.2 SAS® Institute Inc. Cary, NC) with α=0.05. Treatments were the only fixed effect for all analyses, while blocking and trial effects were considered random.

Results and Discussion

Natural Weed Population

Weed coverage before spray applications was approximately 36% and did not differ between treatments (Figure 2). The UAV-IS applications were 3% more precise than broadcast applications (P = 0.016). The precision analysis estimates the accuracy of the UAV-IS to identify and treat weedy areas while leaving non-weedy areas untreated. Although the broadcast treatment missed only 3% of the target weedy area, and the UAV-IS treatment left 15% of the non-weedy area untreated (data not shown), the higher precision in the UAV system was due to the fact that only 80% of the plot was treated, while the broadcast application covered 97% of the plot including 23% of the area that did not have weeds.

The UAV-IS did not achieve a recall value as high as the broadcast applications (Figure 2). Broadcast applications covered almost the entire plot, treating all weeds present, scoring a near maximum recall value of 1. Treating less area with the UAV system, as opposed to the broadcast treatment, increased the weedy area missed by the application (false negatives) by over 10%. Using site-specific management practices increases the risk of missing target weeds due to errors in detection, applications, or both.

There were no differences in the Fscore between UAV and broadcast treatments (Figure 2). The benefit of site-specific management is leaving non-weedy areas untreated, increasing precision. In contrast, the benefit of broadcast applications is ensuring coverage over all weedy patches by treating the entire field, increasing recall. Therefore, despite their differences in precision and recall, both UAV-IS and broadcast treatments exhibited similar application results by obtaining an equivalent balance between these two parameters.

UAV-IS achieved a 20% higher application efficiency over broadcast applications (Figure 2). Site-specific management practices using UAV-IS resulted in less herbicide applied per experimental unit since less non-weedy area was treated consequently increasing UAV’s application’s efficiency.

Surrogate Weed Population

The use of tobacco plants as surrogate weeds allowed creating weed distributions that were more aggregated than the naturally occurring weed populations at the Willow Springs location (Figure 3). Surrogate weed patches covered 6.5 to 8.5% of the area in both UAV-IS and broadcast systems. UAV-IS treated 60% less area compared to the broadcast application, which covered an average of 93% of the plot. This equated to the UAV site-specific treatments being 20% more precise than broadcast treatments.

The broadcast application achieved almost a perfect recall being 25% higher than UAV-IS (Figure 3). UAV applications treated 33% of the plot, missing 26% of the target weedy area. Conversely, broadcast applications only missed 2% of the weedy area.

UAV-IS and broadcast systems had an equivalent Fscore (Figure 3). The broadcast system treated 92% of non-weedy areas (false positives), while UAV-IS treated only 30%. The 26% of weedy areas missed (false negatives) from UAV applications that lowered its recall value were compensated by the high precision of the application. Thus, the application efficiency of UAV-IS was three times higher than broadcast system (Figure 3), and this was favored by the high aggregation of weed coverage in this study, which required only treating 33% of the total plot area with the UAV-IS.

As aggregation of weed patches increases, the application efficiency of UAV systems also increases (San Martín et al. 2015). This explains the dramatic differences in application efficiency between the surrogate weed and natural weed studies, with the former exhibiting highly aggregated and the latter larger and more uniformly distributed weed populations. Visual ratings at 14 and 28 DAT for *K. striata* control showed broadcast applications providing 15-16% more control than UAV-IS applications (Table 1). It is likely, that the differences in control between treatments was due to the lower recall exhibited by UAV-IS, which allowed a considerably higher weedy area not receiving herbicide treatment than the broadcast treatment.

UAV-IS applications caused higher tobacco injury than broadcast applications at both 14 and 28 DAT (Table 1). At 14 DAT, plants treated with UAV-IS exhibited 12% more glufosinate damage than broadcast treated plants, and this difference increased to 25% at 28 DAT. In both systems, injury decreased between evaluation rates, 9 and 22% for UAV-IS and broadcast systems, respectively. Dry weight was reduced 44% in UAV-IS sprayed and only 20% in broadcast sprayed plants when compared to the non-treated control. Injury and growth reduction results confirmed that plants in UAV-IS plots were more negatively affected by glufosinate than those in the broadcast system. The carrier volume of UAV-IS (151 L ha^{-1}) was 20% lower and generated fewer droplets with a higher concentration of glufosinate as compared to the 187 L ha^{-1} carrier volume of the broadcast system likely favoring herbicide absorption by the plant (McKinlay et al. 1972).

Results from the present study indicate integrating UAVs for weed mapping and site-specific management can create an efficient alternative to conventional broadcast weed management practices. The geospatial precision achieved conducting site-specific weed management in this study was obtained without the use of real-time kinematic (RTK) technology. The U.S. Geological Survey (USGS) reports that the accuracy of RTK-GPS location measurement is 3 cm when determined in relationship to a specific geodetic datum (USGS 2016). Perez-Ruiz et al. (2013) utilized a tractor with an RTK-GPS to achieve intra-row chemical weed control while saving approximately 50% herbicide compared to broadcast applications. Incorporating RTK technology into an UAV-IS would significantly increase the accuracy of pesticide sprays, reducing false negatives and increasing recall.

Future research is needed to decrease application height and optimize parameters characterizing UAV pesticide applications. Further research should be conducted to optimize

UAV flight paths based on target weed density and distribution. Different pesticides are available in varying formulations and their influence on UAV based pesticide treatments require investigation. Formulations with high viscosity at the low application volumes used in UAVs might require high pressure levels to ensure adequate nozzle performance. UAVs offer an excellent platform for remote sensing and a unique platform for pesticide application. The integration of these systems together creates a valuable tool for pest management in agricultural and non-agricultural situations.

Acknowledgments

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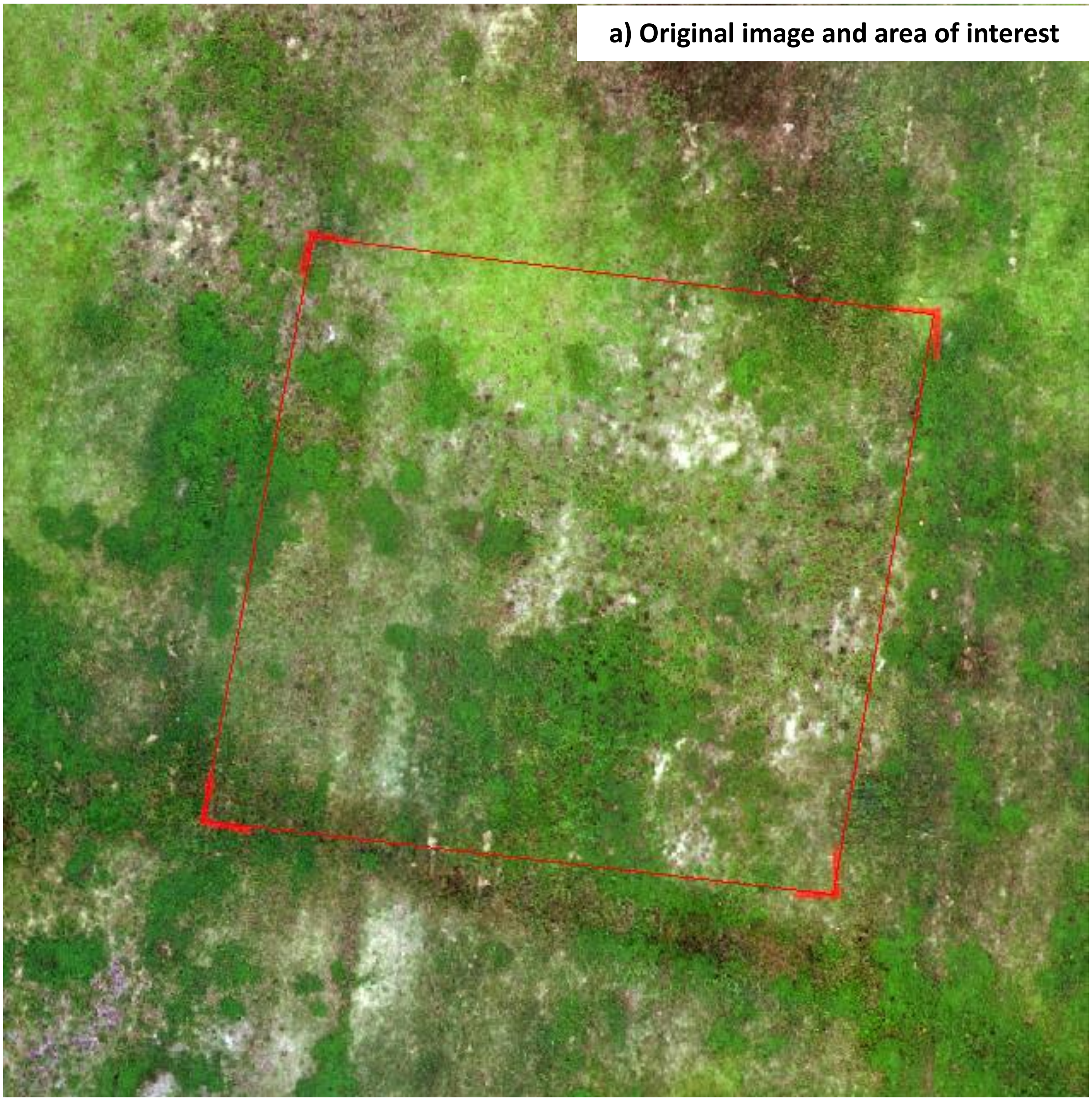
Table 1. Injury at 14 and 28 days after treatment (DAT) and dry weight growth reduction for target species after glufosinate applications with a UAV-IS and conventional broadcast systems based on a non-treated control.

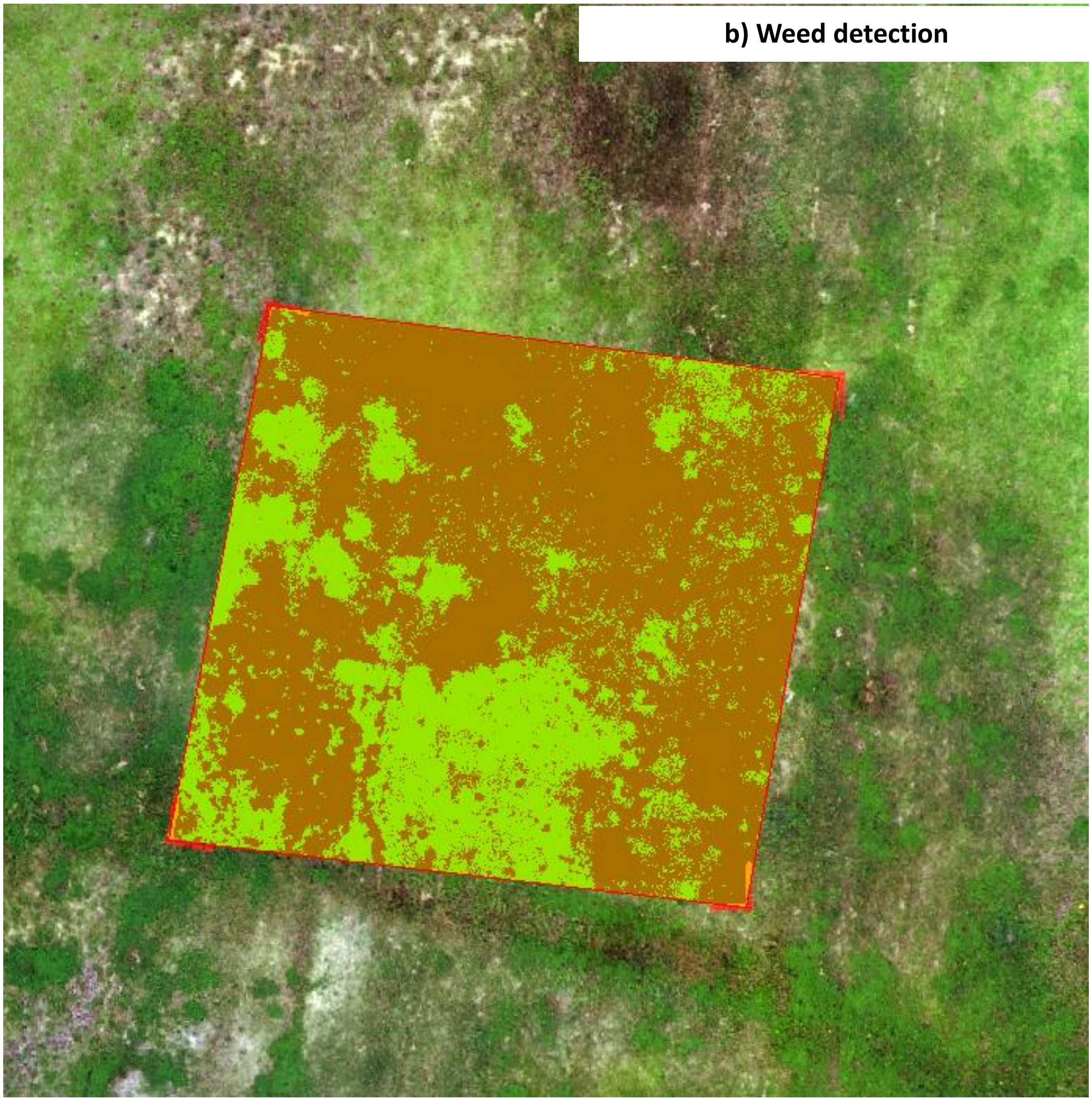
Experiment	Target Species	Application treatment	Injury (%)				Growth Reduction (%)	
			14 DAT		28 DAT			
Natural Weed Populations	*Kummerowia striata*	UAV	81	b[a]	81	b	nd[b]	
		Broadcast	96	a	97	a	nd	
Surrogate Weed Populations	*Nicotiana tabacum*	UAV	93	a	85	a	44	a
		Broadcast	82	b	60	b	20	b

[a] Means followed by different letters within the same column and experiment were statistically different (P<0.001).

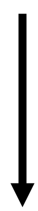
[b] nd: not determined

Figure 1. Supervised image classification was conducted to identify weeds by color differences (a-b). After identifying target areas, GPS coordinates associated with the collected imagery were extracted to create paths of travel for site specific UAV applications (c). UAV data collecting flight missions were conducted to create a new map for post-application analysis (d-e). Overlaying plot boundary (a), weed detection (b), and spray analysis (e) maps allowed quantifying on-target and off-target treated areas to later determine application efficacy and efficiency (f).

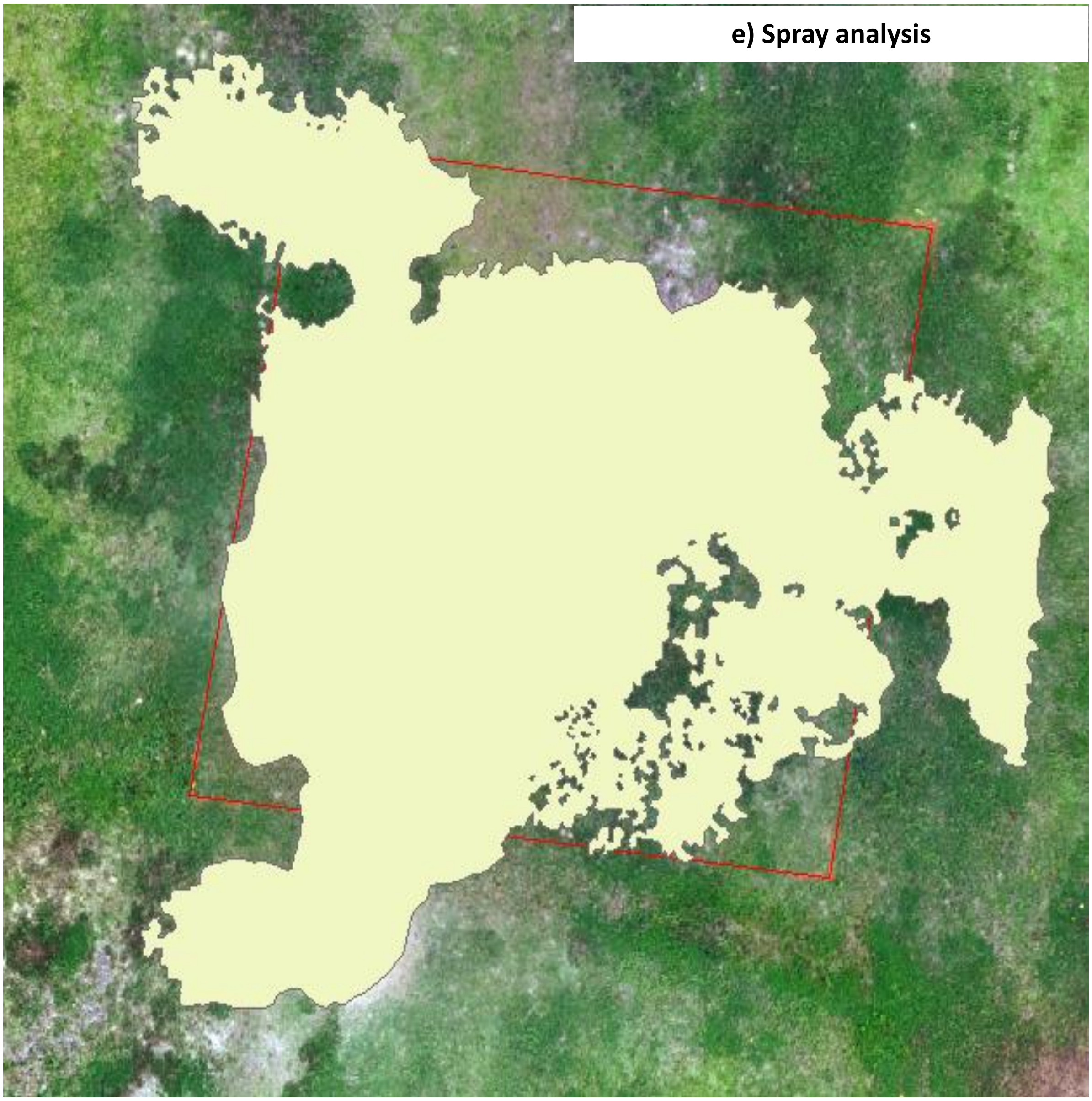

a) Original image and area of interest

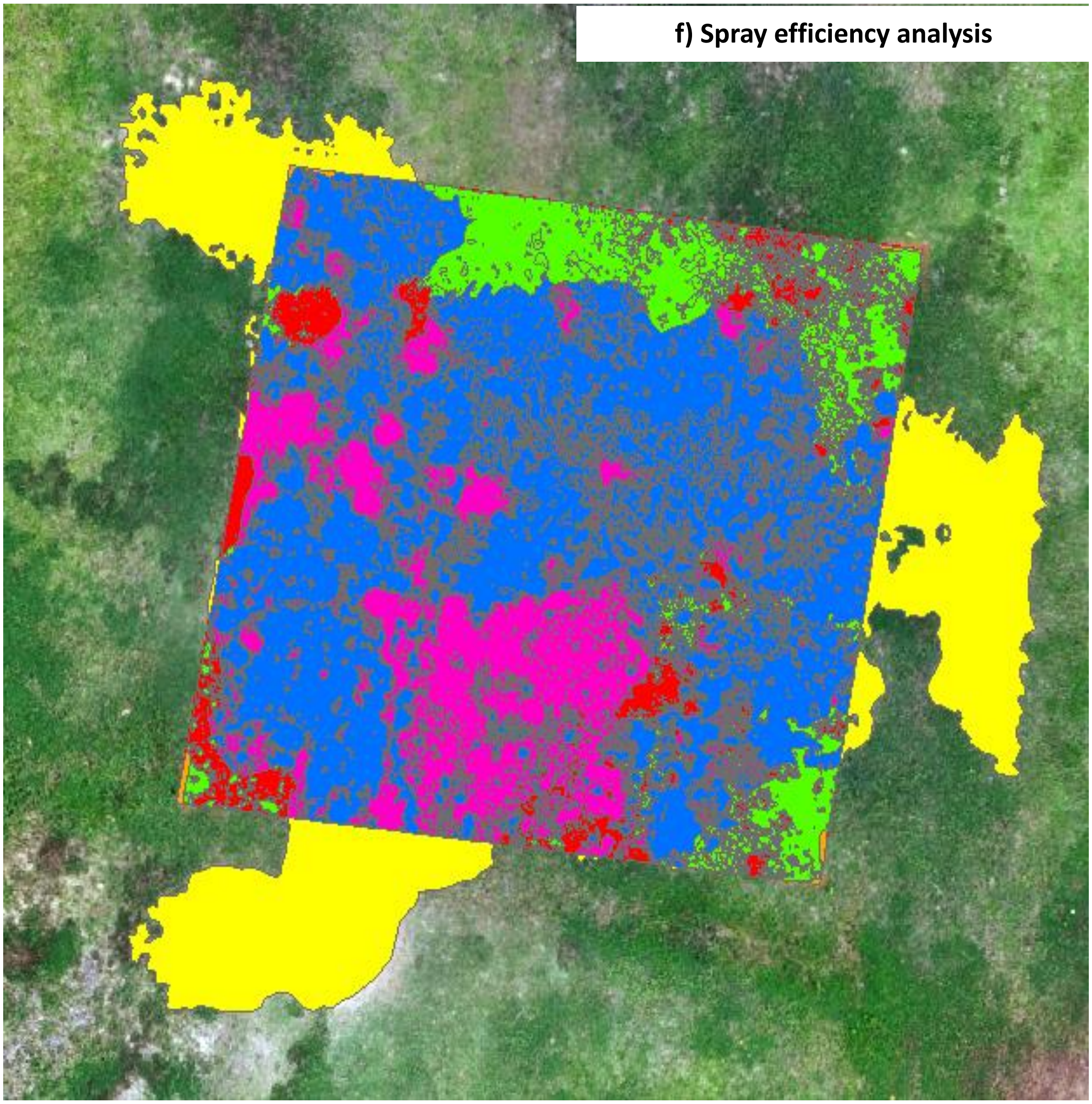

b) Weed detection


c) Flight path




d) Sprayed area


e) Spray analysis


f) Spray efficiency analysis

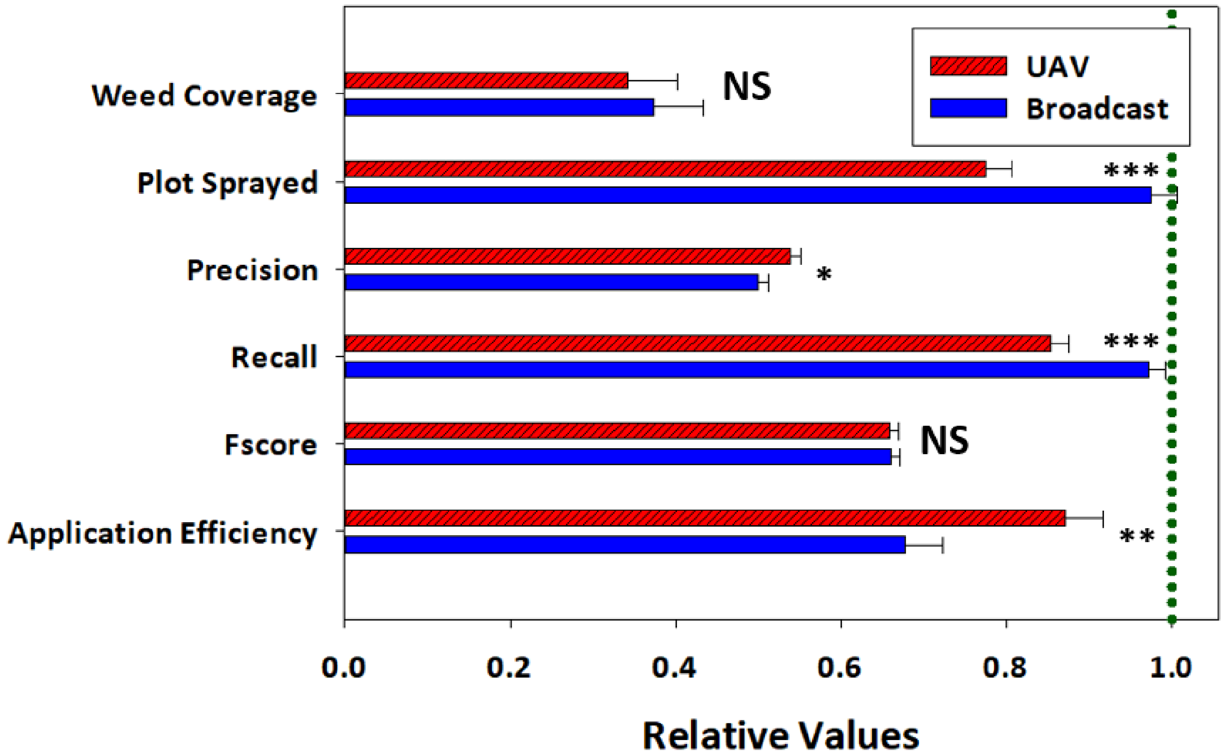


Figure 2. Relative estimates of application indexes for UAV-IS and conventional broadcast treatments of glufosinate in a sod field with natural populations of *Kummerowia striata* in Willow Springs, NC. The dotted line indicates a relative value of 1.0 for each index and is equivalent to the entirety of the experimental unit for weed coverage and plot sprayed. Asterisks represent statistical significance (NS: Non-significant; *, **, *** indicated statistical differences at 0.05, 0.01, and 0.001 significance levels, respectively).

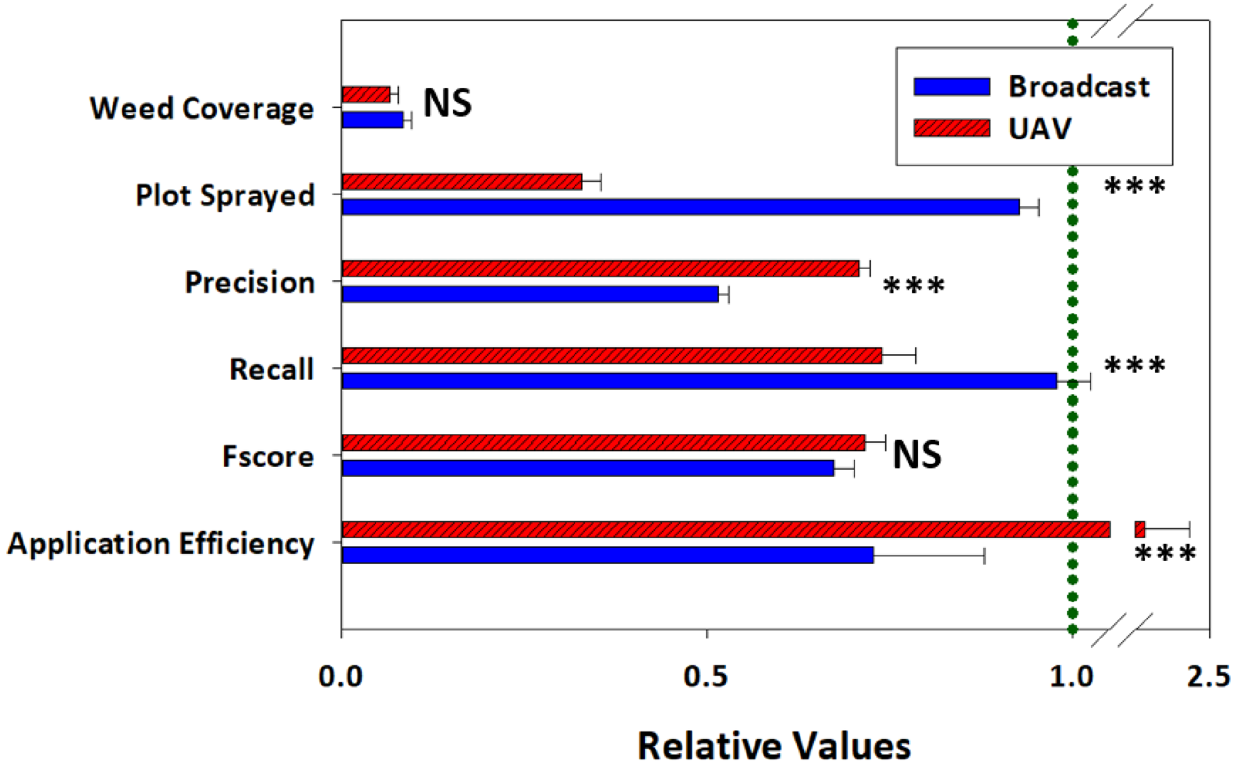


Figure 3. Relative estimates of application indexes for UAV-IS and conventional broadcast treatments of glufosinate in a sod field with surrogate weed populations generated wit *Nicotiana tabacum* plants in Eagle Springs, NC. The dotted line indicates a relative value of 1.0 for each index and is equivalent to the entirety of the experimental unit for weed coverage and plot sprayed. Asterisks represent statistical significance (NS: Non-significant; *, **, *** indicated statistical differences at 0.05, 0.01, and 0.001 significance levels, respectively).

CHAPTER 3: General Conclusions and Recommendations for Future Research

Research Conclusions

The present research project on the usage of unmanned aerial vehicles (UAVs) for aerial applications is one of the first completed in the United States. From the data produced, a consistent decrease in spray coverage was observed as the UAV's application speed increased. This was expected, as the spray volume for all applications, regardless of application speed, remained constant. Increasing application speeds also increased the driftability of smaller spray droplets. Of the spray nozzles tested (e.g. XR, AIXR, and TTI), the XR produced the smallest droplets, which favored the highest coverage, but were also more prone to drift than the AIXR or TTI nozzles. The UAV's propellers favored the downward movement of spray towards the target area. This finding coincided with results from UAV spray studies from China. Regardless of nozzle selection, drift was prevalent up to 5 meters downwind from the target under controlled perpendicular wind conditions produced at a height of 0.25 to 1.75 m above the ground. Wind can occur at any atmospheric height, potentially increasing the range of drift at increased heights. Under high wind conditions, spray coverage at the target was equivalent to coverage achieved under no wind. Even though an application could be conducted under high winds, the variability of coverage also increased, increasing the potential for spray drift. To achieve the best possible coverage, while also reducing the risk for spray drift, AIXR nozzles at an application speed of 3 $m\ s^{-1}$ is recommended.

The conducted field studies of herbicide applications over turfgrass showed an integrated system of two UAVs for weed mapping and spray applications can effectively and efficiently map and treat weedy areas while leaving non-weedy areas untreated. There are errors associated with precision for both remote sensing and spray applications that must be considered to ensure accuracy. The benefits of the UAV-IS avoiding spraying non-weedy areas and broadcast applications ensuring treating all weedy areas compensated each other based on Fscore estimations. The UAV-IS used less herbicide to achieve weed control than the broadcast system. The UAV-IS system increased weed control over the broadcast applications when target weed populations were more aggregated. As weed population aggregation decreased, the efficiency of the UAV-IS system also decreased due to misses of weedy areas. To prevent misses over areas with uniform weed populations, broadcast applications should be conducted. The present research highlights the importance of determining for these new technologies whether weed survival over time might be more detrimental than herbicide savings if an UAV-IS were to be widely used in agricultural systems.

General Conclusions

UAVs offer a new platform for precision agriculture that will complement existing agricultural technologies. An integrated system of UAVs for site-specific weed management has proven to be an effective weed control alternative to broadcast weed management when weed populations are highly aggregated in the interested area. This creates potential for UAV-IS to be adopted to optimize equipment allocation and reduce costs for agricultural operations. During a growing season, the greatest potential for weed interference on crop production is early in the season, when the seed bank is at its largest and conditions favor the germination of planted crops as well as weeds. The first herbicide application for weed management should be carried out by conventional broadcast spray equipment, which would control germinating weeds competing directly with the crop. The integration of UAVs could follow this application to develop weed maps measuring the extent of weed pressure after the initial herbicide application. This proposed scouting method may give growers spatial and temporal information on interfering weed populations that can be used to improve decision making for weed management. Late emergence flushes and escapes of weeds from the previous application will be apparent. Extensive or uniform weed pressure across the field would justify a second broadcast herbicide application, while sparsely populated and highly aggregated weed populations will justify using an UAV sprayer for site-specific weed management. Also, applications can be made even when the crop has reached height and canopy closure levels that impede the use of ground-based equipment. Site-specific weed management practices that characterize the UAV-IS have been shown to reduce applied costs compared to broadcast applications by using a fraction of the amount of herbicide needed to achieve acceptable weed control. Decreasing the herbicide applied, decreases the environmental impact of pesticide applications by reducing the amount active ingredient deposited in the field and under risk for off-target movement from volatilization, spray drift, leaching, and runoff. Subsequent herbicide applications and harvest aid applications can follow the same protocol outlined above for using an UAV-IS to first conduct remote sensing to aid management decisions and then conduct the management practices.

UAV sprayers offer a new method to conduct spray applications over areas of limited access. Some areas of interest for spray applications are impossible to be reached by conventional ground-based equipment, personnel with backpack sprayers, or conventional aerial applications. The versatility of UAV sprayers to take off and land vertically as well as hover in place makes them a very suitable option for areas characterized by limited access. The ability of UAV sprayers to release product at varying heights also increases their potential use in orchards or vineyards, where common liquid pesticide applying practices are conducted with air blast sprayers to achieve the needed coverage within the canopy. UAV sprayers can hover above the canopy where the downward force of the rotors can assist the spray droplets to penetrate the canopy.

Barriers to Adoption

The widespread utilization of UAVs for weed management will depend on the advances of other technologies. One of the main limitations for UAV technology in agriculture today is battery duration. UAV battery duration depends on the UAV specifications, wind conditions, and the battery's capabilities. The small UAV used for remote sensing in this proposed research had a maximum flight time of 30 minutes. Conducting missions during windy conditions drains battery power at a faster rate. Advanced batteries that can store more energy without significantly increasing weight are needed to lengthen individual flight times to cover larger areas without increasing altitude which decreases imagery resolution.

Payload capacity is a second major limiting factor for UAV spray applications. The pesticide-applying UAV used in the proposed research had a spray tank capacity of 10 liters of liquid, equating to 10 kg when using water as the carrier. This allowed for a flight time ranging from 10-20 minutes, depending on how much liquid was in the tank and how fast it was applied. Improving payload capacity will allow for more product to be carried and applied per flight but may be nullified if the battery duration of the UAV will not last long enough to spray the entire payload.

Remote sensing technology has been the driving force for adoption of UAVs in agriculture in the United States. Improving remote sensing technology will allow for better data collected from UAVs to be used to improve decision making for management. Increasing UAV payload capacity could allow for multiple sensors to be attached to an UAV that could collect data simultaneously that will provide multiple data sets that are spatially and temporally correlated. The added weight of multiple sensors increasing the UAV's payload relates back to the limitation of battery duration on how long a flight mission can last without having to land.

The development and application of the global positioning system (GPS) was the original spark for modern precision agriculture that is being used today. In recent times, real-time kinematic (RTK) technology has improved GPS guidance to centimeter accuracy. RTK technology has been fitted to UAVs that have recently become available on the marketplace for commercial use. The increased spatial resolution that RTK offers enhances the precision for remote sensing applications as well as site specific pesticide applications being carried out by UAVs. Since this technology is new and has not been available for long, it is still fairly expensive. As this technology is readily adapted to agriculture as well as other applications, the costs associated with it are expected to decline.

The potential for the unique platform offered from UAVs for data acquisition and management strategies is just starting to be realized. In this age of technology, the generation and advancement of new UAV technologies has far exceeded the rate of adoption and implementation. While different UAVs can be purchased in the marketplace, the optimization of UAV platforms for particular missions is needed. UAV sprayers are available from multiple manufactures who offer differing nozzle configurations and flight parameters from one another. Proven standard configurations may vary depending on the application, but the optimization of these configurations is needed to provide the most use of the technology. The conceptual implication of UAVs for agricultural use has been proven and its widespread adoption is soon to follow, only after the technology has been optimized.