DEVELOPMENT AND EVALUATION OF A PRECISION HERBICIDE APPLICATOR FOR SPOT
APPLICATION OF DICHLOBENIL TO CONTROL HAIR FESCUE IN WILD BLUEBERRY
FIELDS

by

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DEDICATION

For the father, husband, and researcher I am striving to become. One day I will grow into that person, and I'll understand that this research was just a small part of my story. The impact I have on others will always be more valuable than anything I write in books or papers.

Craig MacEachern

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ABSTRACT

Hair fescue (*Festuca filiformis*) is the pest of greatest concern for the Nova Scotian wild blueberry (*Vaccinium angustifolium* Ait.) industry given its rapid spread and lack of effective treatment options. Hair fescue has rapidly spread from 2001 when it was found in only 7% of wild blueberry fields to now having a presence in over 75% of fields throughout the province. Pronamide is currently the only widely employed treatment, making it vulnerable to herbicide resistance. Dichlobenil is a group 29 herbicide registered in wild blueberry though, it has had little implementation for managing hair fescue despite its labeled use for perennial grasses. This study began by exploring the effect of dichlobenil on hair fescue at three rates (4400, 5700, and 7000 g a.i. ha^{-1}). Results demonstrate a similar treatment effectiveness to pronamide and produced significantly greater wild blueberry yields than pronamide at the highest label rate. The study then explored the effect of spot versus broadcast applying dichlobenil. It concluded that there were limited differences between the methods and that spot application could be an important option in reducing dichlobenil product costs which can be as high as $1800 ha^{-1}. Once the efficacy of dichlobenil had been realized, the third study was to develop a precision spot applicator for granular agrochemical. This design retrofitted a Valmar 1255 Twin-Roller so that individual boom sections could be controlled based on the input from a predeveloped prescription map. Modifications included the development of custom valves for controlling product application, a custom control box for reading and sending control signals and various minor alterations to the blower fans, hosing, deflector plates and venturi. In field testing the system, it was determined that the novel applicator had an accuracy, precision, sensitivity, and specificity of 95%, 91%, 99%, and 91% respectively. With the system performing well, the final study calculated the economic benefits of the applicator. The analysis demonstrated that the system reduced per hectare application costs by 62.5% over broadcast application. This resulted in a breakeven point of 47.58 applied hectares after accounting for all costs related to the system.

LIST OF ABBEVIATIONS AND SYMBOLS USED

ABBREVIATIONS USED IN TEXT

BRS – Bistable Rotary Solenoid

CAD – Computer Aided Design

GNSS – Global Navigation Satellite System

GPS – Global Positioning System

ID – Inner Diameter

JD – John Deere

Ph.D. – Doctor of Philosophy

RFID – Radio Frequency Identification

TR – Twin Roller

® – Registered Trademark

™ – Trademark

ABBREVIATIONS USED IN EQUATIONS

A_{farm} – Total farm area

A_{tank} – Total area a single hopper or tank can apply product to

C_{app} – Application cost

C_{ha} – Herbicide cost per hectare

C_i – Investment cost

F_c – Fuel consumption

FN – False Negative

FP – False Positive

P – Payback period

P_{fuel} – Price of fuel

S – Savings (over set time period)

t_{app} – Application time

TN – True Negative

TP – True Positive

t_{drone} – Time to setup and fly drone

t_{refill} – Time to refill hopper or tank

v – travel speed

w – applicator or sprayer boom width

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CHAPTER 1: INTRODUCTION

Wild blueberry (*Vaccinium angustifolium* Ait.) is Canada's most valuable fruit export with a 2022 export value of over $366 million. This represents 32.6% of all fruit exported by the country (Statistics Canada, 2023). Wild blueberry is a perennial crop which, unlike most other field crops it is neither seeded nor planted rather, it is encouraged to spread naturally by underground rhizomes already present in the soil. In Nova Scotia, new wild blueberry stems will emerge from rhizomes in early-spring and grow up to a height of 30 cm by mid July (Farooque et al., 2014). Tip dieback occurs around this point, and the plant will transition from vegetative growth to flower bud development. The plant will then enter a dormant phase in late fall and overwinter ending the non-bearing year. In the second year (bearing year), flower buds will swell, burst, and be pollinated by a host of native and commercial pollinators. Small fruits will develop from the pollinated flowers, beginning as small, hard, and green berries and gradually transitioning to pink, red and finally a blue or black color as they soften (MacEachern, Esau, Schumann, et al., 2023). Ripe berries in Nova Scotia are typically harvested from early August through the middle of September. Given wild blueberry's inherent reliance on rhizomes, seasonal tillage is not an option in this crop. This makes perennial weed management among the greatest challenges faced by growers.

The perennial weed of greatest concern to wild blueberry growers is hair fescue (*Festuca filiformis*). This densely tufted perennial weed is among the most abundant in Nova Scotian fields with a frequency of 75% in fields surveyed between 2017 and 2019 (Lyu et al., 2021). Compounding this issue is the rapid spread of the weed which in 2001 was only observed in 7% of fields (Jensen and Sampson, unpublished data, Lyu et al.,

2021). The nature of the weed itself is a key driver in the spread as single hair fescue tufts can produce over 3000 seeds, which lack primary dormancy, and germinate effectively in the acidic soils of wild blueberry fields (Amen, 1966; White, 2018a, 2020; White & Kumar, 2017). Following hair fescue's seed rain, new seedlings will emerge in the fall and promote the formation of competitive sods which have been shown to reduce wild blueberry yields by over 50% (White, 2019; Zhang, 2017; Zhang et al., 2018).

Conventionally, Nova Scotian wild blueberry growers have relied on preemergence applications of hexazinone and terbacil to manage hair fescue (Ismail & Yarborough, 1982; Jensen & Kimball, 1985; Jensen & Yarborough, 2004). Unfortunately, these herbicides have seen a significant decline in effectiveness in recent years (Jensen & Yarborough, 2004; White, 2019; White & Kumar, 2017; Zhang, 2017; Zhang et al., 2018). Hexazinone-resistant hair fescue biotypes were recently identified (Laforest et al., 2022) and terbacil has demonstrated highly variable effectiveness in more recent studies (White, 2019; White & Zhang, 2021). Other herbicide options such as postemergence foramsulfuron and flazasulfuron have demonstrated hair fescue suppression however, these herbicides share a common mode of action and are a considerable concern regarding resistance management (White & Zhang, 2020; Zhang et al., 2018). For these reasons, most wild blueberry producers rely on pronamide. Pronamide has demonstrated over 90% control of hair fescue (White, 2019; Zhang et al., 2018) however, it is largely the only product seeing widespread implementation and therefore is a major concern for selection for herbicide resistance. This overreliance necessitates the need to address resistance management concerns and find alternative herbicides which are effective at managing hair fescue.

Dichlobenil is a group 29 herbicide which is registered for use in wild blueberry but sees little to no implementation. Limited trials have demonstrated some effectiveness for managing hair fescue (White & Zhang, 2020) however, these trials had only two field sites, inconsistent results, and did not consider the effect of application rate. Beyond the lack of research supporting its use, dichlobenil's lack of implementation for managing hair fescue is further hampered by the fact that it is not specifically listed on the herbicides label. Given the general tolerance of fine leaf fescues to many herbicides, further research is needed to confirm dichlobenil's effectiveness. Even if the herbicide performs well, its use represents a major economic investment for growers as uniform applications at the maximum label rate (7000 g a.i. ha^{-1}) cost over \$1800 ha^{-1} (Esau et al., 2019; Truro Agromart, 2023). Cost reduction methods such as mechanical spot application would represent a significant breakthrough and could serve to provide wild blueberry growers with an additional tool for managing what has become the pest of greatest concern for the Nova Scotian wild blueberry industry (Wild Blueberry Producer's Association of Nova Scotia, 2022).

Spot application of granular agrochemical has yet to have any success in terms of mechanized system development. Most research has focused on variable rate applications based on prescription map inputs. Developments and studies by Chandel et al., (2016), Ishola et al., (2014), Kim et al., (2008), Mirzakhaninafchi et al., (2021), and Tola et al., (2008) have all developed systems to this effect and seen considerable successes. Further, companies such as Kuhn (Bucher Industries AG, Niederweningen, Switzerland) and Valmar (Linamar Corporation, Guelph, Canada) have commercially available offerings ranging in hopper capacity from 0.5 m^3 to 18.7 m^3 and application widths from 7.3 m to

50.0 m. Despite the success of variable rate applicators, there is yet to be a commercially available spot applicator for granular agrochemical, and research has not made significant progress either.

This study builds off the work of Chattha et al., 2014 who developed a spot applicator for granular fertilizer. While their study did publish favorable results, the system had several shortcomings which have limited its practical implementation in the years since. First, their system for actuating individual sections was located at the metering wheels immediately before product was introduced to the venturi. This meant that there was a long mechanical delay between decision and application as the product traveled through the hoses and out to the orifice. While theoretically this delay can be calculated and adjusted for, it assumes that all parameters related to product flow remain consistent. However, turbulence in the hosing, travel times while turning, and changes in product bulk density over time (due to degradation) all complicate and make this calculation unpredictable. Degradation was a particular concern with the Chatta et al., 2014 design as it employed a screw auger to return unapplied product back to the hopper. The auger tended to pulverize returning granules and given that the application rate of any granular product is based on bulk density, the application rate would change independent of any changes to the system. Reducing the decision to application delay and reducing product degradation were the two primary concerns in developing the applicator for this thesis. A successful design would represent the first development of a reliable spot applicator for granular agrochemical in any cropping system.

Throughout this work, five key objectives were used to guide the research and development aspects of this project. The specific objectives are to:

1. Assess the effect of dichlobenil for hair fescue management at varying application rates in Nova Scotian wild blueberry fields

2. Assess the effect of spot applied dichlobenil for hair fescue management in Nova Scotian wild blueberry fields

3. Modify an air boom spreader to accommodate spot application of granular agrochemical

4. Field evaluate the developed applicator based on accuracy, precision, sensitivity, and specificity as well as its ability to manage hair fescue in both spot and broadcast configurations.

5. Quantify the economic potential of spot applied dichlobenil as compared to uniform application and traditional management strategies

The objectives serve as the overarching theme for each of the five novel chapters included in this research (chapters 2 through 6). Given 1) the significant challenge which hair fescue represents to the Nova Scotian wild blueberry industry 2) the concerns over resistance management related to pronamide over usage 3) the uniform application cost of dichlobenil being over $1800 ha^{-1} 4) the lack of commercially available spot applicators for granular agrochemical and 5) the potential cost savings associated with the development of a mechanical spot applicator for dichlobenil, success in the above outlined objectives will serve to have a great impact on the wild blueberry industry and on precision agriculture and farm mechanization more broadly.

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CHAPTER 2: EVALUATION OF DICHLOBENIL FOR HAIR FESCUE (FESTUCA FILIFORMIS POURR.) MANAGEMENT IN WILD BLUEBERRY (VACCINIUM ANGUSTIFOLIUM AIT.)

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2.1   Abstract

Hair fescue is an economically destructive, tuft forming weed common in wild blueberry fields. Current management of fescue is almost completely reliant on pronamide with few other products demonstrating effectiveness. Dichlobenil is a group 29 herbicide registered for use in wild blueberry, though it has seen limited implementation because of its high product cost of over $1800 ha^{-1} and limited research on the effect of varying application rates. To assess the effect of dichlobenil on hair fescue, three rates of dichlobenil (4400, 5700 and 7000 g a.i. ha^{-1}) were compared with pronamide (2240 g a.i. ha^{-1}) and a nontreated control. Each treatment was replicated five times per site across three sites in central Nova Scotia. Dichlobenil had a significant effect on reducing hair fescue vegetative tuft density, flowering tuft density and mean inflorescence at all tested rates compared with

the control. In two of the three sites, the high rate of dichlobenil was not significantly different from pronamide in terms of vegetative tuft density while all three sites were not significantly different in terms of flowering tuft density and mean inflorescence. The high rate of dichlobenil was the only treatment which resulted in significantly more wild blueberry yield than the control treatment. Results demonstrate that dichlobenil is an effective herbicide for managing hair fescue in wild blueberry. The potential for herbicide resistance to industry standard pronamide could be prolonged with integrated dichlobenil applications.

2.2 Introduction

Wild blueberries (*Vaccinium angustifolium* Ait.) are a perennial crop native to northeastern North America. Unlike traditional field crops, they are not seeded or planted but rather, are encouraged to spread through rhizomes already present in the soil. This process can be hastened through the removal of debris and competing vegetation. The life cycle of commercially managed wild blueberries begins with stem emergence in the spring of the first year. The stems then develop and grow up to a height of 0.30 m before tip dieback occurs in late July (Farooque et al., 2014). Leading up to and continuing from tip dieback, the plant will begin to form flower buds. Progressing into late fall, the plants will enter a dormant phase and overwinter. Spring of the second season sees the swelling and bursting of flower buds. Newly opened flowers will be pollinated by a host of native and commercially managed pollinators and fruit formation ensues (Hanes et al., 2015). Fruit first becomes visible in late spring as small, hard and green berries. As the summer progresses, berries will gradually enlarge, become softer, and transition in color from pink to red and finally to a blue, purple or black color dependent on the clone (MacEachern,

Esau, Schumann, et al., 2023). Berries are typically harvested from early August through the middle of September using mechanical harvesters. Following harvest, the plants are left until the weather gets cold, the leaves drop from the plants, and the plants are mowed back to near ground level. This is done as the yields in year two of the plant's development are considerably higher than in any other subsequent years of the plant's lifespan (Eaton & Nams, 2006; MacEachern, Esau, Zaman, et al., 2023). Mowing fields after the plants have entered their dormant phase likewise creates the opportunity to manage several of the more persistent perennial weeds found throughout wild blueberry fields.

Hair fescue is among the most abundant weeds found in Nova Scotian wild blueberry fields with a frequency of 75% in fields surveyed between 2017 and 2019 (Lyu et al., 2021). This densely tufted perennial weed has seen significant spread in recent years as evidenced by the only 7% field frequency observed in 2001 (Lyu et al., 2021). Individual hair fescue tufts can produce up to 3000 seeds, which lack primary dormancy and readily break from the panicle inflorescence (Amen, 1966; White, 2018a, 2020; White & Kumar, 2017). New seedlings emerge in fall following the seed rain (White 2018), contributing to rapid formation of competitive sods that can reduce wild blueberry yield by over 50% (White, 2019; Zhang, 2017; Zhang et al., 2018). Management of hair fescue is, therefore, important for economically viable wild blueberry production in Nova Scotia, Canada.

Hair fescue was traditionally managed with preemergence hexazinone and terbacil applications (Ismail & Yarborough, 1982; Jensen & Kimball, 1985; Jensen & Yarborough, 2004). Hexazinone-resistant hair fescue biotypes, however, have recently been identified (Laforest et al., 2022) and terbacil efficacy is variable in Nova Scotia (White, 2019; White & Zhang, 2021). Hair fescue can be suppressed with postemergence foramsulfuron and

flazasulfuron applications (White & Zhang, 2020; Zhang et al., 2018) though these herbicides share a common mode of action and repeated use is a concern for herbicide resistance management. Therefore, most growers rely on pronamide for hair fescue management. Pronamide provides over 90% control of hair fescue (White, 2019; Zhang et al., 2018) but is expensive (approximately CAD$435.00 ha^{-1}) and growers are often unable to use this herbicide during periods of low crop prices. Repeated use of pronamide also creates concerns for resistance development, necessitating the identification of new herbicide modes of actions that can be used for managing hair fescue.

Dichlobenil is a group 29 granular herbicide currently registered for use in wild blueberries. Dichlobenil provides good control of hair fescue (White and Zhang 2020) but has seen little adoption by wild blueberry growers due to limited use of granular herbicide applicators and a product cost of over CAD$1800 ha^{-1} at the full label rate (Esau et al., 2019). Dichlobenil can however, be spot applied manually or, at a rate of 4400 g a.i. ha^{-1} to 7000 g a.i. ha^{-1}. Applications rates below 7000 g a.i. ha^{-1}, however, have not been evaluated (White & Zhang, 2020). Furthermore, new technological advances are being made in precision granular herbicide application (MacEachern & Esau, 2023), providing opportunity for improved economic viability of dichlobenil use for hair fescue management in wild blueberry.

Given 1) the limited number of effective herbicide modes of action providing acceptable control of hair fescue in wild blueberry, 2) the lack of knowledge of the effect of dichlobenil application rate on hair fescue, and 3) the development of new application technology for granular herbicides such as dichlobenil, the objective of this research was

to evaluate a range of dichlobenil application rates for hair fescue management in wild blueberry fields.

2.3 Materials and Methods

2.3.1 Plot Setup

The experiment was designed to compare multiple dichlobenil (Casoron® G4 Herbicide, MacDermid Agricultural Solutions Inc., Waterbury, CT, USA) application rates to industry standard pronamide (Kerb™ SC herbicide, Corteva Agriscience, Calgary, AB, Canada) applications. The experiment consisted of 5 treatments arranged in a randomized complete block design with 5 blocks, 2m by 4m plot size, and a 1m buffer between adjacent plots. Treatments consisted of 1) nontreated control, 2) pronamide at 2,240 g a.i. ha^{-1}, 3) dichlobenil at 4,400 g a.i. ha^{-1}, 4) dichlobenil at 5,700 g a.i. ha^{-1}, and 5) dichlobenil at 7,000 g a.i. ha^{-1}. The experiment was conducted in 3 wild blueberry fields in central Nova Scotia. Site 1 is in North River (45.464542, -63.212526), site 2 is in Lornevale (45.472619, -63.629979), and site 3 is in Camden (45.300056, -63.183472). Soil composition at each field site can be seen in Table 2-1.

Table 2-1: Soil texture, pH and organic matter in each of the three field sites

	Sand (%)	Silt (%)	Clay (%)	pH	Organic Matter (%)
Site 1	85.7	9.5	7.8	4.49	11.5
Site 2	83.6	9.6	6.8	4.74	12.6
Site 3	81.8	9.1	9.1	4.58	9.8

The experiment was established in November at each site following wild blueberry plant pruning. At all sites, pronamide was applied on November 17, 2020 and dichlobenil on November 18, 2020. Pronamide was applied with a CO_2-pressurized research plot sprayer equipped with four Hypro 12002 ULD orifices calibrated to deliver 300 L ha^{-1} at 276 kPa. Dichlobenil was applied using a Scotts® Wizz™ Year-Round Spreader

(ScottsMiracle-Gro, Marysville, United States). The Wizz™ is a battery operated, handheld spinner-spreader with adjustable application rate and width. In all trials, application width was maintained at 1.00 m while the rate was maintained at one of the three rates defined by the treatments. This meant that for the 2 m wide plots, two passes were made per plot. All product applied with the Wizz™ was pre-weighed to ensure the exact amount of product was applied per plot.

2.3.2 Data Collection

Data collection for hair fescue included living (vegetative) tuft density at the time of herbicide application, vegetative and flowering tuft density in June of the non-bearing and bearing years, and tuft inflorescence number in July of the non-bearing year. A tuft was deemed to be flowering if it had one or more inflorescences emerging from the tuft. Hair fescue tuft density was determined in 6 randomly positioned, 0.5m X 0.5m quadrats plot[-1] and tuft inflorescence number was determined on 10 tufts plot[-1] using a line transect method described by White and Kumar (2017).

Data collection for wild blueberry included stem density in July of the non-bearing year, stem height and flower bud stem[-1] in October of the non-bearing year, and yield in August of the bearing year. Wild blueberry stem density was determined in 9 randomly positioned, 0.15m X 0.15m quadrats plot[-1] and counting the number of stems within. Stem height and flower buds stem[-1] were determined on 30 stems plot[-1] using the same line transect method described above. Yield was determined by harvesting all berries from 2 randomly positioned, 1 m x 1 m quadrats plot[-1].

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2.3.3 Statistical Analysis

All data were analyzed using ANOVA procedure in Minitab (Version 21.2, Minitab LLC, State College, United States). Site, treatment, and the site by treatment interaction were modeled as fixed effects in the analysis, and significance of all effects was based on $\alpha = 0.05$. Data were pooled across sites or analyzed separately pending significance of the site by treatment interaction. Normality was assessed using the pencil-test (Montgomery, 2013) and confirmed with the Anderson-Darling test for normality. Constant variance was assessed by plotting the residuals versus fitted values and observing for the impression of an even band centered around 0. Means separation, where necessary, was conducted using Fisher's least significant difference multiple means comparison at $\alpha = 0.05$.

2.4 Results and Discussion

2.4.1 Hair Fescue

At the time of product application, there were no significant differences ($p > 0.05$, for all sites) in terms of vegetative tuft density with average densities of 41.66, 24.61 and 42.05 tufts m^{-2} for each of sites 1, 2 and 3 respectively. The ANOVA indicated a significant interaction of site and treatment ($P < 0.001$) for vegetative tuft density, flowering tuft density, and mean inflorescence number in the non-bearing year. Consequently, data were analyzed separately for each site (Table 2-2).

Table 2-2: Effect of pronamide and various dichlobenil application rates on hair fescue vegetative tuft density, flowering tuft density, and tuft inflorescence number at three wild blueberry fields (Site 1, Site 2 and Site 3) located in North River, Lornevale and Camden, Nova Scotia, Canada during their non-bearing years

	Vegetative Tuft Density (tufts m^{-2})			Flowering Tuft Density (flowering tufts m^{-2})			Mean tuft inflorescence number		
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
Nontreated control	44.8a	36.00a	56.92a	26.28a	14.4a	31.2a	44.56a	29.12a	18.96a
Pronamide (2,240 g a.i. ha-1)	2.80c	1.08b	2.40e	0.00c	0.12b	0.12c	0.00b	0.00b	0.00b
Low Dichlobenil (4,400 g a.i. ha-1)	24.80b	5.72b	25.88b	5.32b	1.48b	6.80b	2.18b	3.34b	2.40b
Medium Dichlobenil (5,700 g a.i. ha-1)	18.52b	3.08b	18.00c	2.80bc	1.08b	2.92bc	4.22b	3.98b	2.94b
High Dichlobenil (7,000 g a.i. ha-1)	8.40c	3.6b	10.92d	0.68c	0.00b	1.32c	2.52b	1.62b	0.96b

Means within a column followed by the same letter are not significantly different according to Fisher's LSD (P≤0.05)

Across each of the three sites in the non-bearing year, pronamide produced a consistent reduction in vegetative tuft density, flowering tuft density and mean tuft inflorescence number (Table 2-2). The high rate of dichlobenil reduced vegetative tuft density at all three sites and to the same degree as pronamide at sites 1 and 2. The low and medium rates of dichlobenil likewise reduced vegetative tuft density at all three sites though only to the same level as pronamide at site 2. All three rates of dichlobenil reduced flowering tuft density at all sites with the medium and high rates reducing levels to a similar degree as pronamide. The low rate of dichlobenil only reduced flowering tuft density to a similar level as pronamide at site 2. All herbicide treatments reduced mean tuft inflorescence number to a similar level at all sites. Non-bearing year data demonstrated the efficacy of dichlobenil and its few differences from pronamide when applied at 7000 g a.i ha^{-1}. That said, these herbicides can only be applied every two years therefore, it was equally important to assess how they continue to manage hair fescue throughout the bearing year.

In analyzing the bearing year data, the ANOVA indicated a significant interaction of site and treatment ($P < 0.001$) for vegetative tuft density, flowering tuft density, and mean inflorescence number. Consequently, data were analyzed separately for each site (Table 2-3)

Table 2-3: Effect of pronamide and various dichlobenil application rates on hair fescue vegetative tuft density and flowering tuft density, at three wild blueberry fields (Site 1, Site 2 and Site 3) located in North River, Lornevale and Camden, Nova Scotia, Canada during their bearing years

	Vegetative Tuft Density (tufts m^{-2})			Flowering Tuft Density (flowering tufts m^{-2})		
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
Nontreated control	60.00a	40.28a	68.80a	35.46a	18.00a	43.68a
Pronamide (2,240 g a.i. ha-1)	5.46c	2.40b	7.06d	0.00c	0.00b	0.00c
Low Dichlobenil (4,400 g a.i. ha-1)	29.73b	6.93b	32.80b	6.23b	1.75b	8.30b
Medium Dichlobenil (5,700 g a.i. ha-1)	22.93b	8.53b	21.73c	3.41bc	1.31b	3.60bc
High Dichlobenil (7,000 g a.i. ha-1)	9.07c	5.33b	22.66c	0.74c	0.00b	1.50c

Means within a column followed by the same letter are not significantly different according to Fisher's LSD ($P \leq 0.05$)

Pronamide treatments resulted in a consistent reduction in vegetative tuft density and flowering tuft density across all sites (Table 2-3). All three dichlobenil treatments produced significantly lower vegetative tuft and flowering tuft densities than the control. The high rate of dichlobenil performed similarly to pronamide in all variables and sites except for vegetative tuft density at site 3 where it did not reduce tuft density to the same degree. The low and medium rates of dichlobenil performed similarly to pronamide at site 2 in both variables but did not reduce vegetative tuft density to the same degree as pronamide at sites 1 and 3. The medium rate of dichlobenil performed similarly to pronamide in terms of flowering tuft density but the low rate did not reduce this variable to the same level. These results demonstrate that dichlobenil has the potential to manage

hair fescue at variable rates within the recommended application range. Observations were likewise noted that sites 1 and 2 tended to comprise plots with smaller, less established tufts as opposed to the of larger tufts observed at site 3. It is possible that this tuft formation may have led to the discrepancies observed at site 3 in terms of vegetative tuft density. Future work would be required to determine the effect of hair fescue tuft density and tuft size on dichlobenil efficacy.

Dichlobenil efficacy on hair fescue was previously demonstrated by White and Zhang (2020), though their study only evaluated dichlobenil at 7000 g a.i. ha^{-1}. This study therefore not only provides additional data to confirm dichlobenil efficacy, but also provides critical information on the importance of utilizing application rates of 5700 – 7000 g a.i. ha^{-1} to maximize hair fescue control (Table 2-2 and 2-3). Demonstrating efficacy of dichlobenil at lower rates serves as effective means of reducing applications costs and making its implementation in a weed management strategy more appealing to growers. Although reports of pronamide resistance globally are low relative to other herbicides (Heap, 2023), pronamide-resistant annual bluegrass (*Poa annua*) was recently identified in turfgrass in Georgia and Texas, USA (McCullough et al., 2017; Singh et al., 2020) following routine use of pronamide. Hair fescue tufts produce thousands of seeds (White & Kumar, 2017) that lack primary dormancy and readily germinate following the seed rain in late summer and early fall (White, 2018a). Upwards of 8000 seedlings m^{-2} emerge in fall following the seed rain (White, 2018a), and seed banks of this weed are considered transient in wild blueberry fields (White, 2019). Lack of seed dormancy, rapid seedling emergence following the seed rain, and transient seed banks are considered high risk traits for evolution of herbicide resistance (Kumar et al., 2019). Although wild blueberry growers

can suppress hair fescue with pronamide alternatives such as clethodim, glufosinate, foramsulfuron, and flazasulfuron (White, 2022; White & Graham, 2021; White & Kumar, 2017; Zhang et al., 2018), these herbicides do not reduce vegetative tuft density to the same extent as pronamide and dichlobenil as demonstrated by this study. As such, dichlobenil is an important herbicide for future sustainability of hair fescue management due to similar efficacy as pronamide via a different mode of action. However, dichlobenil is prohibitively expensive to apply over large areas, but new technologies focusing on precision application of this herbicide will contribute to identifying financially viable uses of dichlobenil in wild blueberry (Bilodeau et al., 2023; MacEachern & Esau, 2023)

2.4.2 Wild Blueberry

There was a significant site by treatment interaction for wild blueberry stem density and flower bud count stem^{-1} (P < 0.001 and p = 0.007 respectively), and thus data for different sites was analyzed separately (Table 2-4)

Table 2-4: Effect of pronamide and dichlobenil on non-bearing year wild blueberry stem density and flower bud count per stem in North River (Site 1), Lornevale (Site 2) and Camden (Site 3) field sites

Treatment	Mean Wild Blueberry Stem Density (stems m^{-2})			Mean Flower Bud Count Stem^{-1}		
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
Nontreated control	371.29c	704.12c	910.50ab	1.47c	2.86c	2.37c
Pronamide (2240 g a.i. ha^{-1})	652.80b	1150.48a	939.17a	2.76b	3.16bc	3.25b
Low Dichlobenil (4400 g a.i. ha^{-1})	641.93b	995.43b	791.05b	2.78b	3.47ab	3.21b
Medium Dichlobenil (5700 g a.i. ha^{-1})	658.66b	993.50b	837.44ab	3.39a	3.78a	3.70ab
High Dichlobenil (7000 g a.i. ha^{-1})	801.91a	975.70b	899.64ab	3.07ab	3.48ab	4.14a

*Means within a column followed by the same letter are not significantly different according to Fisher's LSD (p ≤ 0.05)

At sites 1 and 2, each of the herbicide treatments resulted in significantly more stems m^{-2} (Table 2-4). This result was not reproduced at site 3 where all treatments resulted

in similar stem densities with the exception of the low dichlobenil rate which had fewer stems. While it cannot be conclusively determined at this stage, the cause of the discrepancy could be due or related to clonal variation within the trial area. Wild blueberry development characteristics can vary significantly between genotypes (Barai et al., 2022) and it is possible that among the five control plots used in site 3, a greater proportion of them may have included clones which produce more stems. The results of sites 1 and 2 make more sense as it can logically be assumed that through a reduction of hair fescue coverage more stems should propagate. Nonetheless, site 3 has been farmed far longer than sites 1 or 2 and the blueberries may have reached saturation in terms of blueberry stem density. More research into these findings would be needed to explore this phenomenon. All herbicide treatments resulted in significantly greater flower bud counts stem^{-1} with the exception of pronamide at site 2. The medium and high rates produced similar flower bud counts at all sites. These result strongly supports the use of dichlobenil in wild blueberry fields as it demonstrates that the level of weed control may have a positive effect on flower bud count. Given the similarities to pronamide across variables, dichlobenil usage is justified given the current level of pronamide implementation.

There was no significant interaction between treatment and site ($P > 0.05$) in terms of yield, data were therefore pooled across sites for analysis (Table 2-5).

Table 2-5: Mean wild blueberry yield by application rate for each of the treatment conditions measured in August 2022 (bearing year)

Treatment	Mean Yield (kg m^{-2})
Nontreated control	0.217b
Pronamide (2240 g a.i. ha^{-1})	0.375ab
Low Dichlobenil (4400 g a.i. ha^{-1})	0.352ab
Medium Dichlobenil (5700 g a.i. ha^{-1})	0.340ab
High Dichlobenil (7000 g a.i. ha^{-1})	0.421a

*Means followed by the same letter are not significantly different according to Fisher's LSD (P≤0.05)

Reduction in hair fescue coverage through dichlobenil applications of 7000 g a.i. ha^{-1} increased wild blueberry yield relative to the nontreated control but not relative to the other herbicide treatments (Table 2-5). Yield data were, however, highly variable which likely limited the ability to separate means. This is common in small plot research in wild blueberry as variability in blueberry plant coverage across plots and natural variability in yield of wild blueberry genets (Hepler & Yarborough, 1991) all affect the ability to detect yield differences among treatments. Factors which may be impacting the variation include lower light conditions for plots located toward the extremes of field edges, reduced herbivory by edge feeders and birds in weedier areas, or reduced pollination in weedier areas. While none of these factors were explored in this study, their effects should be assessed as future works.

2.5   Conclusions

In all trials and across all metrics, the high rate of dichlobenil reduced vegetative tuft density, flower tuft density and tuft inflorescence while increasing wild blueberry stem density, flower bud count and yield. These results clearly demonstrate the potential for

dichlobenil deployment as part of a hair fescue management strategy in wild blueberry. Dichobenil's new mode of action will prove valuable for resistance management and can reduce the industry's reliance on pronamide. Further work is needed to assess whether the additional costs of dichlobenil compared to pronamide are justifiable. That said, its value as an alternative to reduce hair fescue's potential for herbicide resistance should not be undervalued.

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CHAPTER 3: EFFECT OF APPLICATION METHOD ON DICHLOBENIL EFFICACY ON HAIR FESCUE (*FESTUCA FILIFORMIS*) IN WILD BLUEBERRY (*VACCINIUM ANGUSTIFOLIUM* AIT.)

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3.1   Abstract

This study assessed dichlobenil's potential to manage hair fescue in wild blueberry when spot or broadcast applied (7000 g a.i. ha⁻¹) as justification for the development of a precision spot applicator. A randomized complete block design was used to assess the potential of both application methods and results were compared with industry standard pronamide (2240 g a.i. ha⁻¹). Dichlobenil had a significant effect on reducing hair fescue vegetative tuft density, flowering tuft density, and tuft inflorescence number using either application method. Further, both dichlobenil treatments had a significant effect by increasing wild blueberry stem density and flower bud count. There were no significant differences in terms of yield, though the large variation within the sample is the likely cause

for this. The similarities between spot and broadcast applied treatments demonstrate the potential of spot applied dichlobenil. Given dichlobenil's broadcast application cost of $1873 ha^{-1}, hair fescue's average field uniformity of 37%, and the wild blueberry industry's overreliance on pronamide, spot application of dichlobenil has significant potential. This work serves as significant justification for the development of a mechanized precision spot applicator for use in the wild blueberry cropping system.

3.2 Introduction

Wild blueberries (*Vaccinium angustifolium* Ait.) are a perennial woody fruit crop and among eastern Canada's most economically important crops with a farm gate value of $134.7 million in 2021 (Statistics Canada, 2022). The first year of wild blueberry growth is purely vegetative, where stems grow from underground rhizomes from spring through late July. From the end of July, the plant switches to dedicate energy into the development of flower buds. The plant overwinters and in the following spring, flower buds burst, are pollinated, and begin to form fruit. Throughout the summer, fruit transition from green, to red and finally to blue, softening as they mature (MacEachern et al., 2021). Ripe berries are harvested from the middle of August through the middle of September. In late fall the remaining stems are mowed back to ground level and the cycle is repeated. Throughout the two-year production cycle, there are several critical management decisions which must be made with perennial weed management at the forefront.

The perennial weed of greatest concern to the wild blueberry industry is hair fescue (*Festuca filiformis*) with the Wild Blueberry Producers Association of Nova Scotia identifying its management as their number one industry priority since 2019 (Wild Blueberry Producer's Association of Nova Scotia, 2019, 2022). Hair fescue is a densely

tufted perennial grass which, when left unmanaged, tends to form dense sods within wild blueberry fields (Laforest et al., 2022; Lyu et al., 2021; White, 2022; White & Kumar, 2017). Further, hair fescue tends to outcompete wild blueberries and has been shown to reduce yields by over 50 percent (White, 2019; Zhang, 2017; Zhang et al., 2018). In 2001, hair fescue was in only 7 percent of Nova Scotian wild blueberry fields and by 2019 it was in 75 percent of fields (Lyu et al., 2021). Mature hair fescue tufts can produce up to 3000 seeds which readily break from the panicle, lack primary dormancy (Amen, 1966; White, 2018, 2020; White & Kumar, 2017), and are a common contaminant on agricultural equipment such as harvesters (Boyd & White, 2009b). The industry's shift towards flail mowing and away from burn pruning has likewise worsened the problem as hair fescue seeds can be killed by heat but are no longer destroyed as part of the pruning process (White & Boyd, 2016).

Preemergence applications of terbacil and hexazinone have traditionally been used to manage hair fescue. Recent research demonstrates terbacil efficacy to be highly variable in Nova Scotia (White, 2019; White & Zhang, 2021) while hexazinone resistance was shown to be 6.1 times higher in hair fescue biotypes within wild blueberry fields than biotypes from a roadside hair fescue population (Laforest et al., 2022). Postemergence applications of foramsulfuron and flazasulfuron can likewise aid in suppression (White & Zhang, 2020; Zhang et al., 2018) however, their similar modes of action are concerning for herbicide resistance management. Pronamide is the current industry standard and provides >90% control. (White, 2019, 2022; White & Zhang, 2020, 2021). Given its prominence, and lack of employed alternatives, there is concern over the use of pronamide and its potential selection for herbicide resistance. Dichlobenil is a group 29 herbicide which has

shown success at controlling hair fescue in limited trials (White & Zhang, 2020). Its lack of deployment is due largely to its elevated cost of $1873 ha^{-1} (Truro Agromart, 2023). With improved application methods targeted at reducing this cost, dichlobenil has significant potential if its effectiveness can be confirmed.

Spot application has significant potential for managing hair fescue in wild blueberry fields given its tendency to clump together and form patches in fields. Spot application has had considerable success across many cropping systems by reducing the total agrochemical usage without sacrificing treatment quality. Giles & Slaughter (1997) found that spot spraying in orchard crops reduced application volume by 66% to 80% over traditional methods. Esau et al. (2018) demonstrated a 78.5% agrochemical savings when spot spraying moss in wild blueberry. Oebel & Gerhards (2005) looked at the effect of spot spraying weeds in cereals, maize, sugar beet and rapeseed and found up to a 60% herbicide savings for grass weed species and up to a 77% savings for broadleaf weed species. Finally, a review by Gerhards et al. (2022) looked at spot spraying in a variety of cropping systems and noted at least a 50% reduction in spraying costs without incurring detriment in future seasons when compared with traditional methods. Considering that average fescue coverage in wild blueberry fields is only 37% (Lyu et al., 2021), there is a theoretical cost savings of 63% by using spot application. Further, there are significant temporal benefits to spot application as stoppages for refiling product can be reduced considerably.

Given 1) the potential selection for pronamide resistant hair fescue biotypes, 2) dichlobenil's potential to provide an alternative mode of action for managing hair fescue, 3) dichlobenil's high cost of $1873 ha^{-1}, and 4) the lack of research comparing spot and broadcast applied dichlobenil, the objective of this study is to compare the efficacy of

broadcast and spot-applied dichlobenil. This study will serve as the justification for the development of a novel granular spot applicator for spot applying dichlobenil to hair fescue in wild blueberry fields.

3.3 Materials and Methods

3.3.1 Plot Setup

The experiment was designed to compare both spot and broadcast applied dichlobenil applications to industry standard pronamide applications. Four treatments were arranged as a randomized complete block design with 5 blocks. Plot size was 4 m x 4 m and a 1 m buffer was left between adjacent plots. Treatments consisted of 1) nontreated control, 2) pronamide (2,240 g a.i ha^{-1}), 3) spot applied dichlobenil (7,000 g a.i. ha^{-1}) and 4) broadcast applied dichlobenil (7,000 g a.i. ha^{-1}). Experiments were carried out in three commercially managed wild blueberry fields. Site 1 is a 5.45 ha field located in North River, Nova Scotia (45.463790, -63.212680), site 2 is a 2.21 ha field located in Lornevale, Nova Scotia (45.472437, -63.629886) and site 3 is a 6.23 ha field located in in Camden, Nova Scotia (45.299820, -63.183710). The soil composition in all three sites was loamy sand. Details on the composition can be seen in Table 3-1.

Table 3-1: Soil texture, pH and organic matter in each of the three sites

	Sand (%)	Silt (%)	Clay (%)	pH	Organic Matter (%)
Site 1	85.7	9.5	7.8	4.49	11.5
Site 2	83.6	9.6	6.8	4.74	12.6
Site 3	81.8	9.1	9.1	4.58	9.8

Average absolute plot slopes in North River, Lornevale and Camden were 8.98%, 7.41% and 4.85% respectively. Pronamide was applied in all sites on November 17, 2020 while dichlobenil was applied in all sites on November 18, 2020. A CO_2 pressurized research grade sprayer outfitted with four Hypro 12002 ULD orifices calibrated to deliver

300 L ha^{-1} at 276 kPa was used to apply pronamide. A Fertil™ Backpack Dispenser (Simeoni Tecnogreen, Sacile, Italy) and Scotts® Wizz™ Year-Round Spreader (ScottsMiracle-Gro, Marysville, United States) were used to spot and broadcast apply dichlobenil respectively. The Wizz™ is a portable spinner-spreader powered by batteries, featuring adjustable application rate and width. Throughout the experiments, the application width remained constant at 1.00 m, while the rate was set to 175 kg ha^{-1}. Consequently, for the plots measuring 4 m in width, four passes were conducted per plot. To guarantee precision, all product dispensed using the Wizz™ underwent pre-weighing, ensuring the exact amount was applied to each plot. The Fertil™ was likewise pre-calibrated in lab prior to use to ensure the correct amount of product was dispersed on each press of the applicators opening mechanism.

3.3.2 Data Collection

Hair fescue vegetative tuft density data was collected at time of herbicide applications. Vegetative and flowering tuft density was collected in June of the non-bearing and bearing year and tuft inflorescence number was collected in July of the non-bearing year. Densities were determined by counting all tufts within 9, 0.5 m x 0.5 m quadrats per plot. Tuft inflorescence was determined on 10 flowering tufts per plot selected using the line transect method described in White & Kumar, 2017.

Wild blueberry data collection included stem density collected in July of the non-bearing year, flower bud number per stem collected in October of the non-bearing year and fruit yield collected in August of the bearing year. Stem density was determined by counting all stems within 9, 0.15 m x 0.15 m quadrats per plot. Flower bud number was determined by counting the total flowering buds from 30 stems selected using the line

transect method. Yield was determined by harvesting and weighing all berries within 4, 1 m x 1 m quadrats per plot.

3.3.3 Statistical Analysis

Data analysis for all metrics was done using ANOVA in Minitab 21.2 (Minitab LLC, State College, United States). Fixed effects were used to model site, treatment and the site by treatment interaction with significance determined at $\alpha = 0.05$. Dependent on the interaction significance, data were either pooled or analyzed by site. The pencil test (Montgomery, 2013) supported by the Anderson-Darling test for normality were used to determine normality of the data. Constant variance was assured by plotting the residuals versus the fitted values and checking for the impression of an even band centered on 0. Multiple means comparisons were performed using Fisher's least significant difference at $\alpha = 0.05$.

3.4   Results and Discussion

3.4.1 Hair Fescue

At the time of product application, there were no significant differences ($p > 0.05$, for all sites) in terms of vegetative tuft density with average densities of 49.15, 65.33 and 37.04 tufts m^{-2} for each of sites 1, 2 and 3 respectively. For non-bearing year data, there was a significant site by treatment interaction for both the vegetative tuft density and tuft inflorescence number data ($p < 0.001$). For the flowering tuft density there was no significant site by treatment interaction ($p = 0.678$). For this reason, data were presented by site for vegetative tuft density and tuft inflorescence number while it is pooled for flowering tuft density (Table 3-2).

Table 3-2: Effect of pronamide and two dichlobenil application methods on hair fescue vegetative tuft density, flowering tuft density, and tuft inflorescence number at three non-bearing year wild blueberry fields located in North River, Lornevale and Camden, Nova Scotia, Canada

	Vegetative Tuft Density (tufts m^{-2})			Flowering Tuft Density (flowering tufts m^{-2})	Mean tuft inflorescence number (seed heads tuft^{-1})		
	Site 1	Site 2	Site 3	All Sites	Site 1	Site 2	Site 3
Nontreated control	67.00a	72.36a	44.64a	41.08a	43.98a	9.14a	15.02a
Pronamide (2,240 g a.i. ha-1)	12.80c	8.96c	2.12c	0.76b	0.34b	0.00c	0.00b
Spot Dichlobenil (7,000 g a.i. ha-1)	21.4b	9.08c	7.92b	3.76b	6.38b	2.22b	1.20b
Broadcast Dichlobenil (7,000 g a.i. ha-1)	18.68bc	23.64b	7.92b	3.72b	6.72b	1.04bc	1.08b

Means within a column followed by the same letter are not significantly different according to Fisher's LSD (P≤0.05)

Pronamide demonstrated a consistent decrease in vegetative tuft density, flower tuft density, and tuft inflorescence across all study sites (Table 3-2). Spot and broadcast applied dichlobenil likewise reduced vegetative tuft count though not to the same degree as pronamide apart from broadcast dichlobenil in site 1 and spot dichlobenil in site 2. Spot and broadcast applied dichlobenil reduced flowering tuft count to similar degrees as pronamide. Finally, spot and broadcast applied dichlobenil reduced tuft inflorescence number to similar levels as pronamide in sites 1 and 3 though only broadcast dichlobenil reduced inflorescence similar to pronamide in site 2. The only significant difference between spot and broadcast applied dichlobenil across any of the variables was vegetative tuft count in site 2 where spot application had a greater effect on reducing vegetative tuft density. Further, in most sites and variables, it is not significantly different from pronamide applications. This makes it an excellent option to aid in resistance management for a crop which has seen few options available for managing hair fescue. Despite this, pronamide

and dichlobenil can only be applied in wild blueberry every two years and therefore, it is critical to assess the effect of these herbicides on hair fescue in the bearing year as well (Table 3-3).

Table 3-3: Effect of pronamide and two dichlobenil application methods on hair fescue vegetative tuft density, flowering tuft density, and tuft inflorescence number at three bearing year wild blueberry fields located in North River, Lornevale and Camden, Nova Scotia, Canada

	Vegetative Tuft Density (tufts m$^{-2)}$			Flowering Tuft Density (flowering tufts m^{-2})		
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
Nontreated control	73.16a	87.2a	60.72a	41.68a	36.88a	18.92a
Pronamide (2,240 g a.i. ha-1)	11.56b	14.76c	2.24d	0.00b	0.00b	0.00b
Spot Dichlobenil (7,000) g a.i. ha-1)	18.32b	20.44c	20.52b	2.92b	6.58b	5.20b
Broadcast Dichlobenil (7,000 g a.i. ha-1)	16.88b	32.52b	12.80c	2.76b	6.58b	5.20b

Means within a column followed by the same letter are not significantly different according to Fisher's LSD (P≤0.05)

Pronamide produced a consistent decrease in hair fescue's vegetative tuft density, flower tuft density, and tuft inflorescence at all sites, as demonstrated in Table 3-3. Notably, both spot and broadcast applications of dichlobenil produced comparable reductions in vegetative tuft density at site 1. However, in contrast, spot applications of dichlobenil led to greater reductions in vegetative tuft density compared to broadcast applications at site 2, while broadcast dichlobenil resulted in greater reductions in vegetative tuft density than spot applications at site 3. It's worth noting that reductions in flowering tuft density were consistent across all herbicide treatments at each respective site. Dichlobenil's potential to reduce hair fescue is encouraging as no products other than pronamide have demonstrated control similar to this study. Herbicides such as terbacil, foramsulfuron and clethodim have seen suppression in terms of reducing flowering tuft

density (White, 2019; White & Graham, 2021; White & Zhang, 2021), though the degree of treatment in terms of vegetative tuft density was not as successful as dichlobenil.

In comparing the bearing and non-bearing year data, spot applied plots had greater vegetative tuft density increases than broadcast applied plots between years. On average, broadcast applied plots had an increase of 19.2% while spot applied plots had an increase of 35.2%. This result does make sense, as no application buffer was used when spot applying dichlobenil, meaning that non-infested areas will not receive any herbicide making those locations an excellent place for seedling recruitment. Given dichlobenil's persistence in soils (Miller et al., 1966; Sheets et al., 1968), it is understandable that broadcast treatments will see reduced increase in vegetative tufts over spot treatments. Future work with spot treated dichlobenil should consider using a larger buffer around applied tufts to account for seed dispersal from plants not killed by the herbicides. What is conclusive is that both spot and broadcast applications of dichlobenil had significant potential to reduce hair fescue vegetative tuft density to a similar degree as industry standard pronamide. That said, more research should be done to explore the long-term effects of spot and broadcast application on hair fescue control.

In comparing the effects of broadcast and spot applied dichlobenil, there were only marginal differences observed across both the bearing and non-bearing year. The results demonstrate the considerable potential of spot applied dichlobenil not only to reduce application costs, but to improve resistance management with respect to pronamide. As pronamide is currently the only widely employed herbicide for managing hair fescue in Nova Scotia, dichlobenil can help by providing an alternative product, with a separate mode of action. By cycling these two products year on year, it is likely that the lifespan of

both products can be elongated. As for spot application, future work should consider mechanized approaches for applying dichlobenil as the over $1800 ha^{-1} cost will not be achievable for most growers. Despite this, hair fescue coverage in Nova Scotian wild blueberry field is on average 37% (Lyu et al., 2021) leaving a theoretical average cost savings of 63% through spot application.

3.4.2 Wild Blueberry

There was no significant interaction present between site and treatment for each of wild blueberry stem density, flower buds per stem or yield (p = 0.246, p = 0.580 and p = 0.883 respectively). Results of the pooled data can be seen in Table 3-4.

Table 3-4: Effect of pronamide and two dichlobenil application methods on wild blueberry stem density, flower buds per stem and yield at three fields in North River, Lornevale and Camden Nova Scotia in late fall 2021 (non-bearing year)

Treatment	Stem Density (stems m^{-2})	Flower buds per stem	Yield (kg m^{-2})
Nontreated control	970.00c	2.92b	0.416a
Broadcast Pronamide (2240 g a.i. ha^{-1})	1413.33a	3.81a	0.557a
Spot Dichlobenil (7000 g a.i. ha^{-1})	1273.33b	3.94a	0.573a
Broadcast Dichlobenil (7000 g a.i. ha^{-1})	1348.00ab	4.13a	0.617a

Means within a column followed by the same letter are not significantly different according to Fisher's LSD (P≤0.05)

Pronamide and the broadcast application of dichlobenil resulted in the most substantial increase in wild blueberry stem density, although all treatments yielded comparable increases in the number of flower buds per stem (Table 3-4). Spot applications of dichlobenil led to relatively lower increases in stem density, possibly due to the potential to miss some tufts with this application method. Despite the improvements in stem density and the number of flower buds per stem, the overall wild blueberry yield remained consistent across all treatments, averaging 0.540 g m^{-2} (5400 kg ha^{-1}). While there were no

significant differences among the wild blueberry yield data, it should be noted that it is not unusual to encounter lack of yield response to weed control in small plot trials since hexazinone and other herbicides have been widely adopted for use in commercial fields (Boyd et al., 2014; Boyd & White, 2010; Kennedy et al., 2010; White & Kumar, 2017). Further, it is well established that increases in stem density, flower bud count and yield will increase with subsequent effective herbicide applications though not necessarily in each application cycle (Eaton, 1994). For this reason, it is encouraging that stem density and flower bud count increased with each herbicide treatment as it demonstrates that the removal of competing weeds had a positive effect on wild blueberry development. It is likely that with similar management, subsequent years will see improvements to the yield as well.

3.5   Conclusions

Based on the analyzed data, the effectiveness of spot applied dichlobenil can be confirmed. In terms of hair fescue management and effect on wild blueberry plants, there were limited differences observed between pronamide, spot, and broadcast applied dichlobenil. That said, pronamide remains the superior option given its substantially reduced broadcast application cost of $435.00 ha^{-1} compared with $1873.00 ha^{-1} for dichlobenil. Further, the industry's overreliance on pronamide and the potential selection for herbicide resistance supports the notion that alternative herbicides need to be implemented to prolong the lifespan of pronamide. Despite this, spot application remains a plausible means of cost reduction for dichlobenil applications with the results of this study supporting its implementation There are currently no commercially available spot

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applicators for spot applying granular agrochemicals on a large scale. This work supports the feasibility of such a development and demonstrates the need moving forward.

Future applicator developments should consider the requirement for a buffer around spot applied hair fescue tufts to reduce seedling recruitment. While hair fescue hasn't been studied exclusively, research has found that seeds are typically dispersed within 1 m of the parent plant. This is based off a variety of factors including plant height, seed weight, seed shape and wind speeds (Boyd & White, 2009). Despite the buffer requirement, the feasibility of spot applied dichlobenil along with its significant cost saving potential justify future development in this area.

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CHAPTER 4: DEVELOPMENT OF A NOVEL PRECISION APPLICATOR FOR SPOT TREATMENT OF GRANULAR AGROCHEMICAL

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4.1   Abstract

While spot spraying has gained increasing popularity in recent years, spot application of granule agrochemical has seen little development. Despite the potential for the technology, there currently exists no commercially available granular applicators capable of spot application. Therefore, the goal of this study was to design, build, and lab evaluate a precision applicator for spot applying granular agrochemical. The design incorporated a John Deere RC2000 with a custom control box, recirculation system, and electrically actuated valves. All components were modified to fit a Valmar 1255 Twin-Roller. The system receives inputs from a predeveloped prescription map and can actuate each of the twelve valves separately to provide individual orifice control. Casoron® G4 was used as the testing agrochemical and in cycling the product pneumatically for one hour incurred

no significant product degradation (p = 0.110). In lab evaluations, the applicator encountered zero errors in reading prescription maps and actuating the correct valves accordingly. Further, the granule recycling system had zero instances where product built up in the lines or jammed the valves. In all, this project represents the first successful development of a precision granular spot applicator for any cropping system.

4.2 Introduction

Research into granular agrochemical application has largely centered around variable rate technologies. These technologies are typically prescription map based and allow the user to alter the application rate throughout a field in real time based on the map. Maps can be developed for a variety of purposes and based off a variety of parameters such as yield, slope, soil moisture, pest pressure or any other spatially referenced parameter (Schumann, 2010). Chandel et al. (2016) developed a variable rate fertilizer applicator that could adjust application rates detailed by a prescription map with accuracies ranging from 89.3% to 98.1% in terms of applied rate to target rate. Kim et al. (2008) developed a similar variable rate applicator for use in rice. Again, their applicator was able to vary rates of fertilizer based on a prescription map with an accuracy ranging from 81.9% to 97.4%. Tola et al. (2008) modified a granular applicator to accommodate variable rate application. Their system was able to maintain application rates within ± 5% of the target rate with a 0.95-1.90 s delay required to make any changes to the application rate. Mirzakhaninafchi et al. (2021) developed a variable rate seed drill that maintained a coefficient of variation of 2.34% to 5.10% in terms of applied rate to target rate based on setup parameters. Ishola et al. (2014) developed a variable rate applicator for oil palm based on radio frequency identification (RFID). RFID tags were affixed to trees and fertilizer rates were adjusted

automatically based on defined rates for each tree. The average inaccuracy achieved by their system was 0.74 m.

Today there are several commercially available applicators which can accommodate variable rate applications. Of the available options, Kuhn (Bucher Industries AG, Niederweningen, Switzerland) and Valmar (Linamar Corporation, Guelph, Canada) are among the larger, with offerings ranging in hopper capacity from 0.5 m^3 to 18.7 m^3 and application widths from 7.3 m to 50.0 m. Despite the plethora of commercial variable rate options for granular products, there has yet to be significant progress made toward a commercially viable granular spot applicator. Spot application would offer the unique potential to not only vary rate throughout a field, but the potential to turn on/off individual boom orifices to achieve a greater level of precision.

Spot application of granular products in field crops is largely unexplored in literature though Zaman et al. (2005), did develop a spot applicator for variable rate nitrogen in citrus groves. Their system used prescription maps based on the ultrasonically sensed volume of tree canopies to vary fertilizer rates throughout the grove. Their system avoided application in areas without trees or areas with smaller trees which in effect is spot application. That said, this approach would not translate to field crops where the goal is to provide sectional control within the application extents.

The basis for this work builds off the study done by Chattha et al. (2014), which explored the potential for spot application of granular fertilizer in wild blueberry. While their study demonstrated the significant potential of spot application of granules, their applicator design had several technical limitations which restricted its practical functionality. First, their decision system utilised pneumatic actuators to control product

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flow immediately after the metering wheel. This meant that when a positive detection was made, there was a delay of between 4.92 and 7.39 seconds before product was applied. The variability comes from a variety of factors including the length of hose the product must travel through, the air flow coming from the blower fan as well as the composition of the product being applied. For instance, the further the orifice is from the venturi, the farther the product must travel and the longer time that travel will take. This in theory can be calculated and accounted for however, that assumes that all other variables related to the flow remain constant. However, there are several reasons why the constant flow assumption is not reliable. First, the velocity of air flowing from the blower fan is variable due to turbulence in the hosing. Second, when travelling in a straight line, the delay between detection and application may be sufficient. However, when turning, the distance between the sensor and the orifice will change and the time it takes to travel to the detected point will likewise change. This will result in product being applied in incorrect areas or missing targets entirely if reliant on a static delay. This could potentially be mitigated by GNSS integration however this is an unnecessary complication if the delay can be avoided entirely. Finally, the composition of the applied material will likewise play a critical role in the delay timing. This was demonstrated in the results of Chattha et al. (2014) where delay time differences for a single orifice were as high as 1.31 seconds between clay filler and fertilizer. This equates to an on-ground difference in application point of 1.74 m at a ground speed of 4.8 km hr^{-1}. While a bulk density component could be added to the calculation to mitigate this effect, it won't solve the problem entirely and adds another variable in the calculation of the delay. For these reasons the major focus of this project was to mitigate or even remove the effect of the delay in the system.

The second major issue with the design used in Chattha et al. (2014) was the use of a screw auger to return unapplied product to the hopper. In testing the system, granules conveyed with the screw auger tended to get crushed between the cover and the screw itself. This resulted in significant product degradation and would result in changes to the application rate independent of any changes to the software inputs defining the application rate. As a further point of complication, by crushing the granules and altering the bulk density of the returned product, the delay timing of the system would likewise change. For these reasons, a design which did not alter the composition of the granules would be necessary in future iterations of the spot applicator.

The applicator produced in this work was designed to target hair fescue (*Festuca filiformis*) in wild blueberry fields. Hair fescue is a densely tufted perennial weed which has quickly become the pest of greatest concern for Nova Scotian wild blueberry producers (Wild Blueberry Producer's Association of Nova Scotia, 2022). The weed has rapidly spread since 2001 where it was only found in 7% of fields to being found in over 75% of fields by 2019 (Lyu et al., 2021). The dense sods formed by hair fescue can reduce wild blueberry yields by over 50% (White, 2019). Currently, pronamide is the only product which is widely employed for managing hair fescue in Canadian wild blueberry fields. Pronamide provides over 90% control of hair fescue (White, 2019; Zhang et al., 2018) though it does have some technical limitations in the form of its strict application window, temperature sensitivity, and cost (Corteva Agriscience, 2021; Truro Agromart, 2023). Further, being that it is the only product with widespread implementation in hair fescue management, herbicide resistance mitigation needs to be considered. Dichlobenil is the only registered alternative to pronamide which has demonstrated the ability to significantly

reduce hair fescue tuft density (MacEachern, 2023; White & Zhang, 2020). That said, its implementation remains limited due to its granular composition and elevated cost of over $1800 ha^{-1} for a broadcast application (Truro Agromart, 2023). Despite this, dichlobenil has potential if a suitable means of cost reduction such as spot application can be realized. Considering hair fescue's average field uniformity is only 37% (Lyu et al., 2021), there is a theoretical cost savings of 63% achievable through spot application.

Given 1) The rapid spread and economically destructive nature of hair fescue in wild blueberry fields, 2) the wild blueberry industry's overreliance on pronamide and the potential selection for herbicide resistance, 3) dichlobenil's significant potential for managing hair fescue, 4) dichlobenil's uniform application cost of $1873.19 ha^{-1} and 5) the lack of commercially available spot applicators for granular agrochemical along with the shortcomings of previous designs; the objective of this study was to develop and lab evaluate a precision applicator for spot applying dichlobenil in wild blueberry. Such a development would serve to significantly reduce application costs and could be a viable solution for spot applying alternative granular agrochemicals in a variety of cropping systems.

4.3   Materials and Methods

4.3.1   Granular Degradation Trials

To determine a suitable recirculation method for the Casoron® G4 granules, a series of tests were carried out to assess product degradation. As the pneumatic product delivery system was already inherent to the applicator, this was the preferred option for recycling the product as it would reduce system complication and upgrade costs. A small-scale pneumatic system was developed to recirculate granules continuously to assess their

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degradation potential. The system (Figure 4-1) consisted of 4.87 m of 31.75 mm inner

diameter (ID) spiral flex hose, a 38.1 mm x 38.1 mm x 12.7 mm ABS Y-fitting and a 360

mm x 150 mm x 430 mm collection funnel. Compressed air was introduced at the Y-fitting

from a booster tank which fluctuated from 5.38 to 8.20 bar throughout the experiment. The

booster tank was charged by a DeVilbiss 445 series compressor pump (DV Systems,

Barrie, Canada). The air speed observed during the experiment ranged from 29 to 44 m s^{-1}. This air speed is approximately 3.5 to 5 times greater than what is achievable with the

applicator and was chosen to assess an extreme scenario and provide a considerable safety

factor.
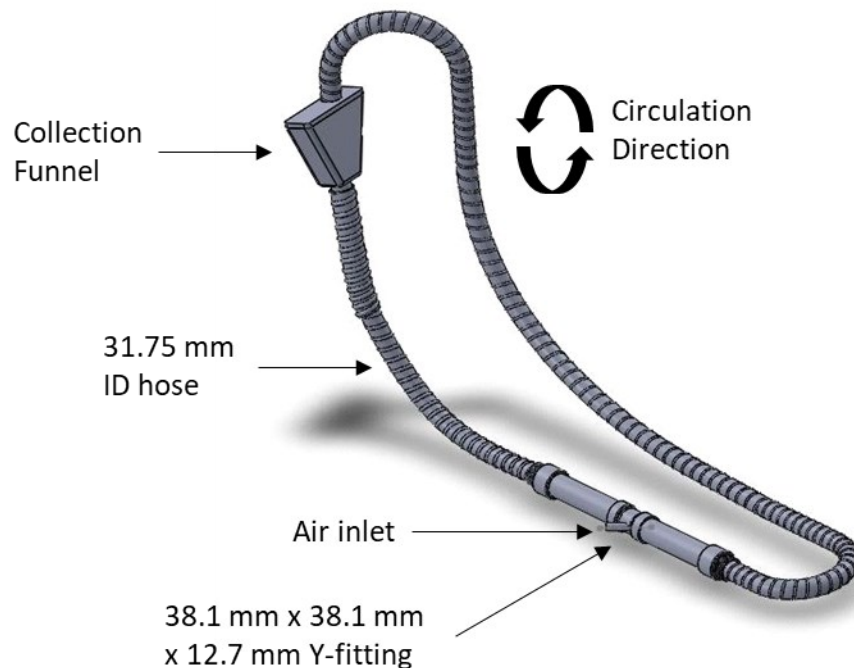
Figure 4-1: Computer aided design (CAD) drawing of pneumatic recirculation system used to assess granule robustness

Three different mediums were selected for analysis, Casoron® G4, 9-30-11 NPK

MESZ fertilizer, and clay filler. Casoron® G4 is comprised of 50-70% silicon dioxide, 10-

20% aluminium dioxide, 4% dichlobenil, 1-5% diiron trioxide, 1-5% magnesium oxide, 1-

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5% calcium oxide, 0.1-1% kaolin and 0.1-1% titanium dioxide (Macdermid, 2015). The fertilizer is comprised of 9% nitrogen, 30% phosphate, 11% potash, 0.4 % magnesium, 7.9% sulfur, 0.8% zinc and 40.9% clay filler and other trace minerals and micronutrients (Sollio Agriculture, 2018). The clay filler is comprised of <3% copper sulfate, <0.7% zinc sulfate and <0.3% zinc with the rest being the clay itself (Graymont, 2021).

One litre of granules were measured out and the bulk density was analyzed from nine 100 mL samples. The granules were then introduced to the cycling apparatus and cycled pneumatically for one hour. Following cycling, the granules were collected and once again, nine 100 mL samples were analyzed according to their bulk density. This was repeated 3 times for each granule. The basis of the analysis is that, if granules were degrading, the bulk densities would be significantly greater following cycling. In addition to the bulk density, 25 randomly selected granules were measured between their two furthest vertices both before and after the cycling period. For both measurements, results were compared with a two-sample t-test on whether the difference between means was less than zero, with significance determined at $\alpha = 0.05$.

4.3.2 Applicator Considerations

The basis for the design of the spot applicator was a Valmar 1255 Twin Roller. Specifications for the stock configuration of this applicator are shown in Table 4-1.

Table 4-1: Specifications for stock Valmar 1255 Twin Roller

Component	Description
Material	Stainless steel
Hopper	0.51 m^3
Boom Width	7.31 m
Boom Height	Adjustable (0.56 – 0.86 m)
Boom Type	Self-levelling
Boom Orifices	12
Hosing	31.75 mm ID spiral flex
Fan Impeller	0.46 m
Impeller rpm	3,200-4,000 rpm
Impeller Drive	Honda GX 270 (6.3 kW at 3600 rpm net power)
Metering	Ground driven
Metering Drive	Hydraulic motor
Sections	2 metering (left boom, right boom)
Rollers	12 and 28 groove options
Height	1.82 m
Width (closed)	2.08 m
Length	2.61 m
Weight	489.88 kg

The applicator is configured to convey product pneumatically using a combination of a venturi, a rear mounted blower fan and a Honda GX 270 gas engine (Honda Motor Co., Ltd., Tokyo, Japan). The first decision point in the design of the applicator was to determine whether this conveyance system could be used as part of a recirculation system. However, this is only feasible if the product can sustain the forces associated with recycling the product through the system. If the product breaks down during recycling, then the application rate will change independent of any changes to the system. A trial was therefore set up to test Casoron® G4 and its resistance to degradation.

4.3.3 Recirculation System

The stock configuration of the applicator utilised 31.75 mm ID spiral flex hosing to convey product from the venturi to each of the 12 boom orifices. To assess the potential

for product recirculation using the stock blower fan, additional hosing was connected at the boom orifices to return product to the hopper. The length of additional hosing varied from 2.50 to 5.50 m dependant on the distance the orifice was from the hopper. The stock configuration uses a 1:1 gearing ratio between the motor and blower fan. In initial testing, there was product buildup in the return lines as the product made its way back to the hopper. For this reason, the gearing ratio was adjusted to 1.2:1. This moved the peak rpm of the blower fan from 3600 to 4320. After the adjustment there was no observed buildup in the system.

4.3.4 Valve System

Custom valves were designed as a means of directing product flow either onto the deflector plates or back through the recirculation hoses (Figure 4-2).
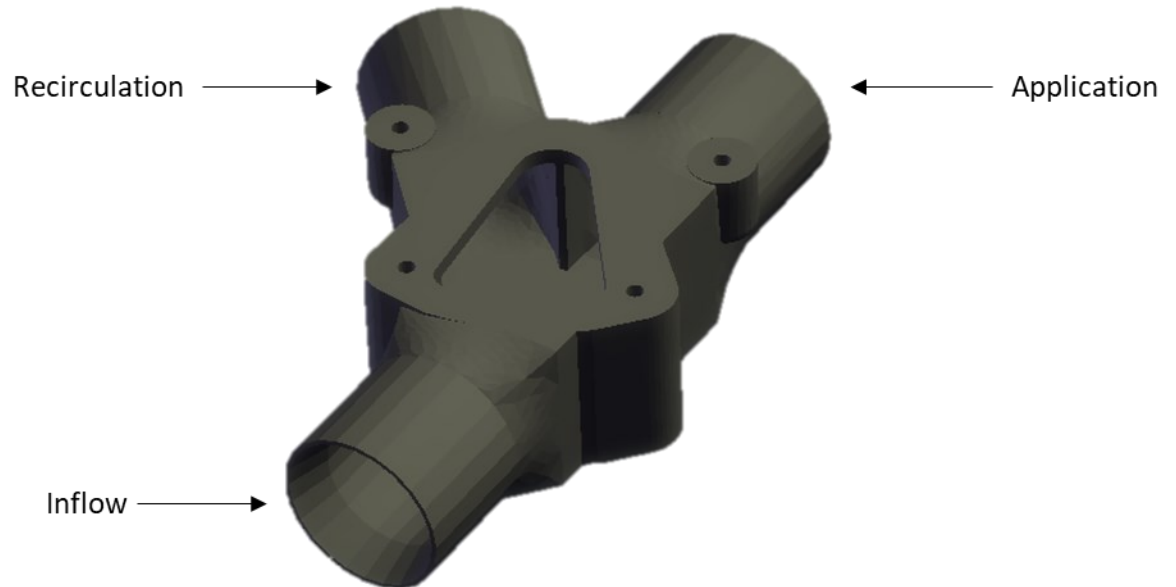
Figure 4-2:Computer aided design (CAD) drawing of the custom valves with the top retaining cover and internal gate removed

The inflow and application ports are in line with one another to have as little effect on product flow as possible. As deflector plates are used in the design, it is imperative that the velocity of the product within the hoses is maintained to ensure proper product fanning. The recirculation hose is set at a 42° angle from the inline ports. Each of the ports has an outer diameter of 31.75 mm and hoses were stretched slightly so that the ports sat inside the hoses. All hoses were affixed to the valves with hose clamps. The inner diameter of the ports is 25 mm but tapers to 29.25 mm at the port edges to have minimal impact on product flow. A metal gate affixed to a Geeplus BRS50C39-6 bistable rotary solenoid (BRS) (Geeplus, Beckenham, United Kingdom) was placed inside the central chamber of the valve. The BRSs operate at 24 V and rotate the gate 30° between two positions within the chamber. The switch between positions occurs in less than 10 ms. The two gate positions exclude product flow from either the recirculation or application port depending on the input signal.

4.3.5   Control System

The control system was designed in three parts. The first utilised a John Deere (JD) RC2000 rate controller, Starfire 6000 receiver, SF3 correction signal, Gen-4 display and swath control (John Deere, Moline, United States). RC2000 settings can be observed in Appendix 4-1. This set of hardware was selected so that prescription maps could be read, and signals could be sent to each of the 12 boom orifices based on their georeferenced position. Georeferencing was done using a combination of the Starfire 6000 receiver and the SF3 correction signal. This system has previously demonstrated accuracies of $\pm$ 73.8 mm in wild blueberry fields (Esau et al., 2021). Given the novelty of the developed applicator, the RC2000 does not support spot applicators. For this reason, the rate controller

was configured as a liquid constant flow, self propelled sprayer. It should be noted that the georeferencing of the orifice positions does not use this denomination, rather, orifice locations were set up as a tow-behind sprayer so that the theoretical orifice locations would adjust accordingly while cornering. This was done in the display software and not the rate controller software. The use of the liquid constant flow setting was essential as it allowed for several pressure and flow gauges to be bypassed in the software. In alternative configurations, the JD software considers these essential checks and will shut off the system if the checks are not within a defined range. Swath control is likewise a vital component of the design as sectional control is not possible without it. Prescription maps were developed using the methodology described in Bilodeau et al., 2023. Using the maps, the system sends up to 12 (one for each boom section), 12 V signals when the georeferenced orifice locations enter a management zone where product is required.

The second component of the control system receives signals from the input system, processes them, and sends a second signal to actuate the orifices. This is performed based on the state change of the incoming signals from either 0 to 12 V or from 12 to 0 V. Six Arduino UNO R3 microcontrollers (one for every two boom sections) check for this state change and in combination with six Pololu Dual G2 High-Power Motor Drivers (Pololu Corporation, Las Vegas, United States) control the sending of either a +24 or -24 V pulse to the BRSs. Pulse lengths of 50 ms were used as this is still five times longer than the rated actuation time and mitigates overheating of the solenoid coils. The 24 V power was provided by an SEC America Model 695CE (SEC America Corporation, South Burlington, United States) high powered 12-24 V DC-DC boost convertor connected directly with the tractor's battery. Control logic for the valves can be seen in Table 4-2.

Table 4-2: Control logic governing valve actuation

Input Signal Voltage Change	Voltage to Solenoid	Orifice Position
0 to 12 V	+24 V	Application
12 to 0 V	-24 V	Recirculation

Product application rate was controlled by an Accu-Rate Controller Model 307583 (Rawson Control Systems Incorporated, Oelwein, United States). Based on the entered parameters, the system controls a hydraulic metering device which, in combination with a wheel speed sensor, maintains the application at the desired rate. In all tests involving Casoron® G4, the system was run at 175 kg ha^{-1} to match the maximum application rate for wild blueberries (Perennia, 2019). The system was calibrated using the controller's built in calibrate function which runs the metering device for a defined distance based on a fixed ground speed. Granules were collected from each of the orifices and weighed. Based on the measured weight and theoretical application area, the system was adjusted to ensure all orifices were applying the correct amount of product.

With each of the systems functioning in isolation, interfacing the systems was the final stage of development. The DC-DC boost converter, RC2000 controller, JD display and Accu-Rate controller were all mounted in the cabin of a Case IH Vestrum 130 (Case IH, Felton, United States). The Starfire 6000 was mounted on the roof of the tractor and orifice positions were georeferenced to its mounted location. All wiring was run out the back window port of the tractor, along the tow bar and into a weathertight control box mounted on the side of the applicator. All the circuitry controlling valve actuation was located inside the control box. Twelve signal wires were run out the back of the control

box to provide control voltage for the solenoids. A CAD drawing of the applicator can be seen in Figure 4-3.
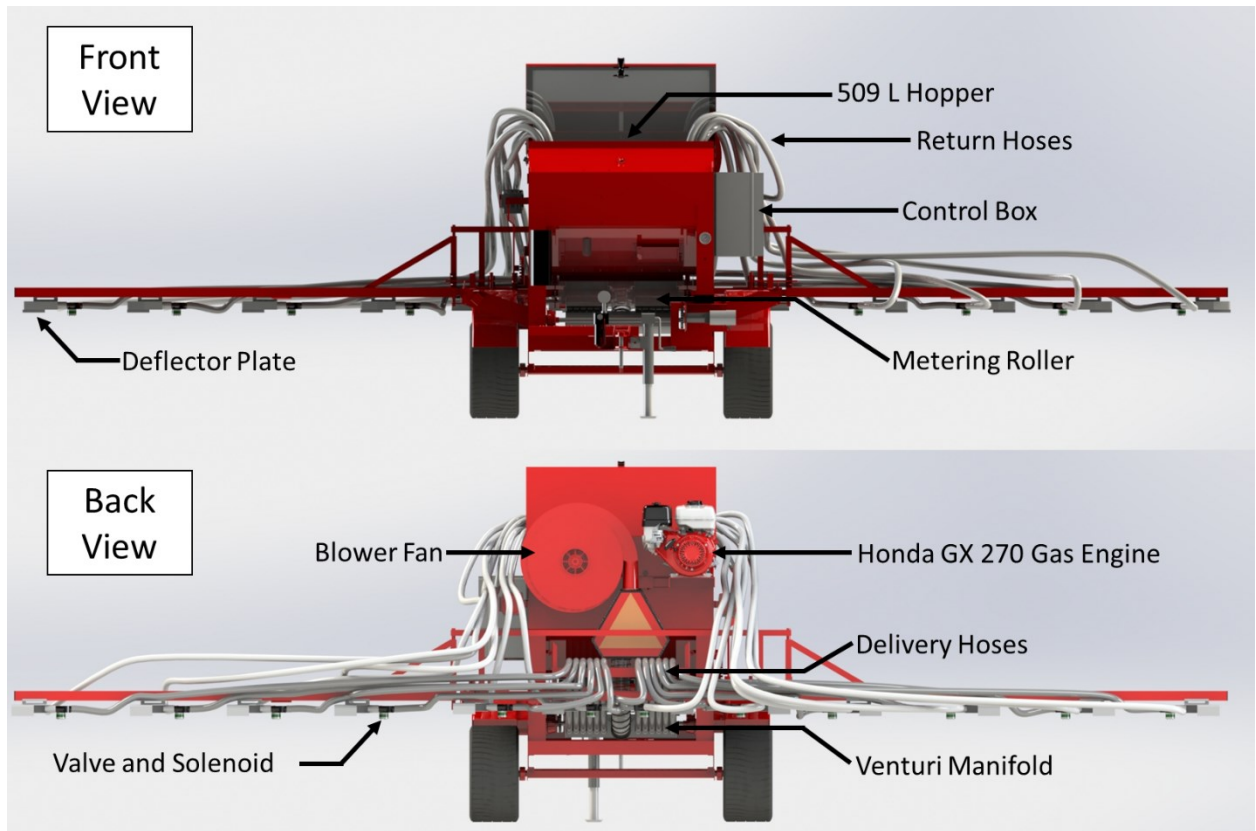
Figure 4-3: Computer aided design (CAD) drawing of the developed applicator showing both a front (top) and back (bottom) view

4.3.6 Lab Evaluation of Applicator

The developed applicator was lab evaluated to ensure product could be recycled without any blockages occurring within the system. To do this, the valves were left on recirculation and the system was run for one hour. The total number of blockages were recorded, and the experiment was repeated five times. A similar approach was used to evaluate the valves. Product was cycled for one hour and valves were manually switched

every minute. The total number of blockages and failures of the valves were recorded over the duration of the trial.

Valve actuation was evaluated using a prescription map of a testing site at Dalhousie Agricultural Campus in Bible Hill, Nova Scotia (Figure 4-4). Arbitrary polygons were drawn within the testing site boundaries to represent hair fescue.

Figure 4-4: Prescription map of parking lot at Dalhousie Agricultural Campus, Bible Hill, Nova Scotia, Canada with arbitrarily drawn polygons for lab evaluating the applicators control and actuation systems. The green polygon simulates the non-fescue areas and the orange polygons simulate the fescue areas.

The prescription was then driven to ensure the proper valves were opening and closing in the correct locations. A 50 m swath was defined within the testing site and the track was driven. At 10 randomly selected distances within the swath, all valves were checked to see if they were in the correct position based on the polygons from the prescription map. This trial was repeated 5 times with unique distances selected in each

replicate. Throughout the trial, no product was applied, though the blower fan and all other components of the system were switched on.

4.4 Results and Discussion

4.4.1 Granular Degradation Trial

Casoron® G4 bulk density was not altered during cycling (Table 4-3) and granule size was similar before and after cycling (Table 4-4). Fertilizer and clay filler, however, had greater bulk density and smaller granule length after cycling (Table 4-3 and 4-4), suggesting these products degraded because of physical stresses incurred during cycling. That said, the change in fertilizer granule length was only marginally significant.

Table 4-3: Results of the cycling analysis showing the mean bulk density before and after cycling as well as the p-value denoting the significance of the difference between values (two-sample t-test)

Granule	Sampling Time	Mean Bulk Density (g L^{-1})	Significance of Difference
Casoron	Before Cycling	659.7	$p = 0.110$
	After Cycling	663.4	
Fertilizer	Before Cycling	1,015.8	$p < 0.001$
	After Cycling	1,064.5	
Clay Filler	Before Cycling	1,548.9	$p < 0.001$
	After Cycling	1,682.3	

Table 4-4: Results of the cycling analysis showing the mean granule length (measure between the two furthest vertices) before and after cycling as well as the p-value denoting the significance of the difference between values (two-sample t-test)

Granule	Sampling Time	Granule Length (mm)	Significance of Difference
Casoron	Before Cycling	0.98	$p = 0.378$
	After Cycling	0.96	
Fertilizer	Before Cycling	4.32	$p = 0.086$
	After Cycling	3.91	
Clay Filler	Before Cycling	4.44	$p = 0.003$
	After Cycling	3.72	

Results from the fertilizer granule measurement however, may be somewhat misleading as visual observation of the post-cycling granules determined that the potash granules within the mixture were almost entirely broken apart, leaving only a fine dust. This meant that these particles could not be measured accurately and were therefore omitted from the post-cycling analysis. Inclusion of these particles would likely lead to the conclusion that significant product breakdown did occur. In all, the cycling analysis confirmed Casoron® G4's potential to be cycled pneumatically without significant product breakdown. This result justified the resulting development of the applicator using a pneumatic recycling system. The hope that the system could likewise serve as an applicator for fertilizer seems unlikely given the brittle nature of the mixture, in particular the potash granules. Alternative fertilizer brands or mixtures may help to mitigate this issue and allow the applicator to apply fertilizer spot specifically.

4.4.2 Lab Evaluation of Applicator

With the valves left in the recycle position and product cycled for one hour, there were zero observed instances where product built up or back flowed within the delivery or return lines. Similarly, when testing the valves, there were zero observed instances where

the valves jammed or failed to open/close when toggled on the JD display. Previous iterations of the design encountered difficulties in both areas so success in these trials was deemed sufficient as a final design. Those previous tests involved longer return hoses, a reduced pulley ratio on the blower fan, valves with longer chambers/gates, and valves which allowed for product to buildup behind the gate's mounting point. With these issues resolved, the final design performed perfectly in isolation.

In testing the prescription maps and the ability for the system to turn on/off the correct orifices, there were zero instances where the system failed to operate as intended. This result demonstrated the potential of the mapping approach and the ability for the system to be highly precise and accurate. Given the success of the design, future work should look at in-field evaluations of the system at full scale.

4.5   Conclusions

In analyzing the robustness of Casoron® G4 granules there was no significant product degradation when cycled pneumatically for one hour. This result was confirmed using both bulk density and by measuring particle size. This result supports the use of pneumatic conveyance as a means of recycling product for accommodating spot application with the precision applicator.

With the applicators valves left in the recycle position and product cycled for one hour, there were zero observed instances where product built up or back flowed within the delivery or return lines. Similarly, when testing the valves, there were zero observed instances where the valves jammed or failed to open/close when toggled on the JD display.

In testing the prescription maps and the ability for the system to turn on/off the correct orifices, there were zero instances where the system failed to operate as intended. This result demonstrated the potential of the mapping approach and the ability for the system to be highly precise and accurate. Given the success of the design, future work should look at in-field evaluations of the system at full scale.

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4.7 Appendix

Appendix 4-1: RC2000 settings used throughout development and testing

RC2000 Settings	
Application Width	7.32 m
Machine Type	Self Propelled Sprayer
Application Mode	Liquid Constant Flow
Number of Sections	12
Section Valve Type	3-wire
Equal Width Sections	yes
Fence Rows Enabled	no
Section Width	0.61 m
Pressure Sensor	no
Agitator Valve	no
Flow Return Installed	no
Control Valve Type	none
Flowmeter Calibration	8000
Flowmeter Pulse Units	37.85 L
Tank Capacity	0
Current Level	0
Low Tank Level	0
Tank Fill Monitor	0
Preset Rate Value	175
Rate Bump	0
Rate Selection	Map Based
Rate Smoothing	15%
Decimal Shift	1
Off Rate Alarm	30
Alarm?	no
Minimum Flow Rate	0

CHAPTER 5: MECHANIZED SPOT APPLICATION OF GRANULAR AGROCHEMICAL: A FIELD EVALUATION OF A NOVEL PRECISION SPOT APPLICATOR

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5.1 Abstract

This study was a field evaluation of a novel precision spot applicator for granular agrochemical. Specifically, the design was evaluated on its potential to spot specifically apply Casoron® G4 to patches of hair fescue in wild blueberry fields. Sticky traps were placed in both target and non-target locations within the field and predeveloped prescriptions were driven. Overall, system performance was encouraging with an accuracy, precision, sensitivity, and specificity of 95, 91, 99 and 91 percent respectively. The system was likewise assessed on its potential to spot apply Casoron® G4 while maintaining a similar level of hair fescue management to conventional broadcast application. In this trial, there were no significant differences in terms of hair fescue vegetative tuft count between spot and broadcast applied product ($p < 0.05$ at all sites). In

all, the system performance was highly encouraging and represents the first successful development of a precision spot applicator for any cropping system. For wild blueberry specifically, the system has the potential to considerably reduce the cost of granular agrochemical applications while providing a cost-effective option for managing hair fescue.

5.2 Introduction

Wild blueberry is a perennial crop typically produced on a biennial basis. After harvesting, fields are mowed back to near ground level and the plants will enter a dormant phase in preparation for overwintering. It is at this point in late fall when preemergence herbicides are typically applied, especially those targeting hair fescue (*Festuca filiformis*). Hair fescue is an invasive and densely tufted perennial grass which has quickly become the pest of greatest concern for the Nova Scotian wild blueberry industry (Laforest et al., 2022; Porter et al., 2020; Wild Blueberry Producer's Association of Nova Scotia, 2019, 2022). In 2001, hair fescue was found in only 7% of Nova Scotian wild blueberry fields and by 2019, it was found in over 75% (Lyu et al., 2021). The rapid spread is attributable to the over 3000 seeds which a single hair fescue tuft can produce (White & Kumar, 2017). These seeds readily break from the panicle, lack primary dormancy, and spread easily through both primary and secondary dispersal (Amen, 1966; Boyd & White, 2009a; White, 2018a, 2020; White & Kumar, 2017). Being that wild blueberry is a no tillage crop, herbicides are the only effective means of controlling this economically destructive weed.

Pronamide (group 3) is the most widely used herbicide for controlling hair fescue in wild blueberry and has demonstrated over 90% reduction in hair fescue vegetative tuft density in wild blueberry (White, 2019; Zhang et al., 2018). Other herbicides such as

terbacil, hexazinone, foramsulfuron, flazasulfuron and clethodim have demonstrated an ability to reduce inflorescence numbers however, they are not as effective as pronamide in terms of reducing vegetative tufts (White, 2019, 2022; White & Graham, 2021; White & Zhang, 2020, 2021). As of now, hair fescue resistance to pronamide in wild blueberry fields has yet to be documented though, the industries nearly complete reliance on the product makes it an excellent candidate. Alternative products with similar reductions in vegetative tuft counts are needed to prolong the lifespan of pronamide and continue to ensure that the industry has options for managing hair fescue.

Dichlobenil is a group 29 herbicide sold under the trade name Casoron® G4. Casoron® G4 is a granular formulation which like pronamide, should be applied in wild blueberry during late fall for controlling hair fescue. The findings of chapters 2 and 3 have demonstrated dichlobenil's similar effectiveness to pronamide in terms of reduction in vegetative tuft density, flowering tuft density and reduction in inflorescence number. Despite the benefits, the significant product costs (over \$1800 ha^{-1} at 175 kg ha^{-1}) of Casoron® G4 have limited its implementation in the wild blueberry cropping system. That said, precision agriculture and spot application solutions could serve to make this product more appealing to growers.

While spot sprayers are becoming more prevalent in agriculture for a variety of applications, granular spot applicators have seen very little development. The majority of research into granular applicators has been done on variable rate applications (Alameen et al., 2019; Chandel et al., 2016; Fulton et al., 2001; Iida et al., 1998; Ishola et al., 2014; Kim et al., 2008; Mirzakhaninafchi et al., 2021; Tola et al., 2008; Yinyan et al., 2018) however, these developments do not allow for sectional control within the application width. If an

applicator is to perform similarly to a spot sprayer it needs to offer this sectional control. One such device was developed by Chattha et al. (2014), who demonstrated the potential of an individual orifice controlled applicator. Their applicator was designed to avoid applying fertilizer in bare spots within wild blueberry fields. While the design was accurate in isolated trails, the applicator did not see any uptake from the industry due to its technical limitations in terms of inconsistent delay timings and granule degradation resulting from the product return auger. The design of the applicator under evaluation in this study built off many of the concepts proposed by Chattha et al. (2014).

A novel precision spot applicator (Figure 5-1) was developed throughout a previous work (Chapter 4) which is capable of spot applying granular agrochemical. The applicator reads a predeveloped prescription map and can individually control the application of product across 12 orifices. The potential to spot apply agrochemical on hair fescue is particularly appealing given that primary seed dispersal causes patches of hair fescue to form within fields. By mapping these patches against the wild blueberry plants there is significant potential for cost mitigation.

Figure 5-1: Computer aided design drawing of novel spot applicator

Given 1) The wild blueberry industry's overreliance on pronamide and the potential of dichlobenil to manage hair fescue, 2) the need to find a cost effective means of applying dichlobenil and 3) the recent development of a novel spot applicator for spot applying granular agrochemical, the goal of this study was to field evaluate the spot applicator by determining its application accuracy and precision while assessing the potential of dichlobenil applied via the novel applicator for controlling hair fescue.

5.3   Materials and Methods

The spot applicator evaluated in this study was a modification of a Valmar 1255 Twin Roller (Linamar Corporation, Guelph, Canada). Modifications included the addition of custom control valves for product diversion located at the orifice, modifications to the blower fan to increase airflow and the addition of a custom control system for controlling product application based on prescription maps. Full details on the modifications are

available in Chapter 4. In all, the system provides individual orifice control for 12 orifices across a 7.31 m wide application width. Orifice control was determined by prescription maps developed using the technique described in Bilodeau et al., 2023.

The field evaluation trial of the applicator was set up to compare spot application to broadcast application and the effect of applicator-applied Casoron® G4 on hair fescue vegetative tuft density. The experiment was a randomized complete block design across three commercially managed fields, with three blocks and three treatments per block (Spot application, broadcast application, and no application). The three selected sites were all located in Nova Scotia's Colchester County. Site 1 is a 1.96 ha field section located in Murray Siding (45.369061, -63.206695), site 2 is a 1.33 ha field section located in Murray Siding (45.364875, -63.213123), and site 3 is a 3.00 ha field located in Kemptown (45.500496, -63.102192). Developed prescription maps for each site can be seen in Figure 5-2.
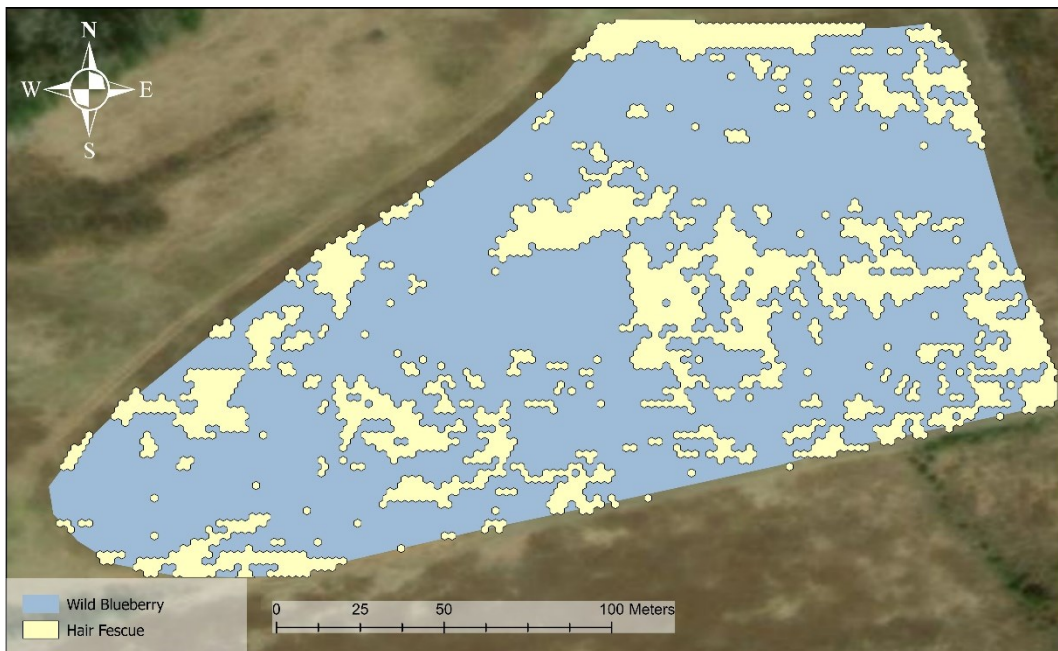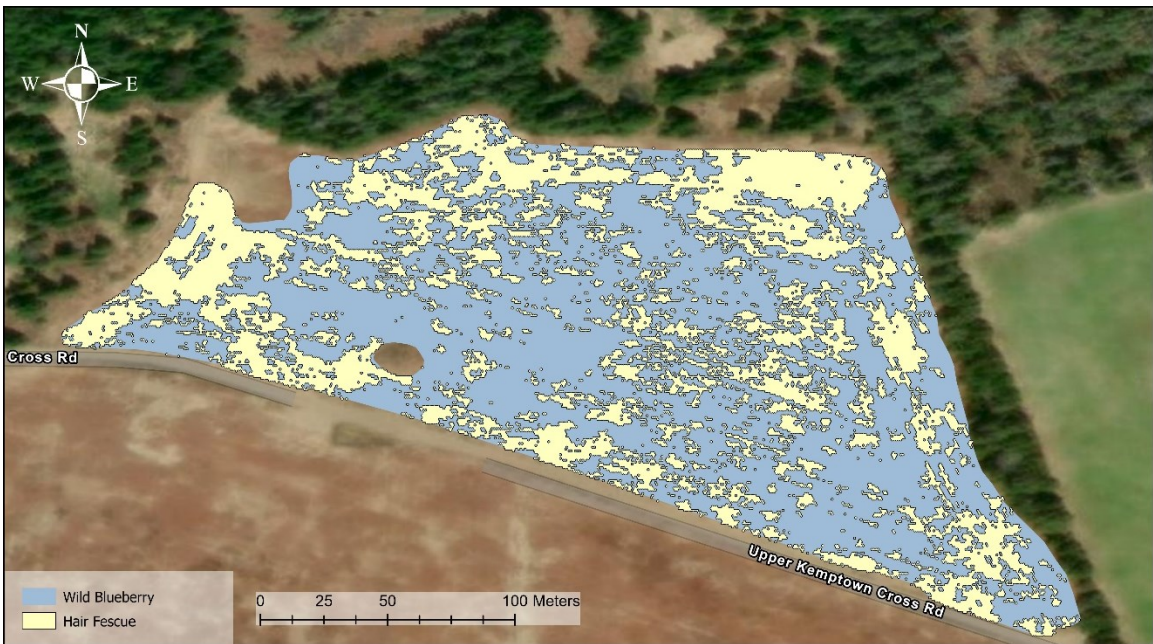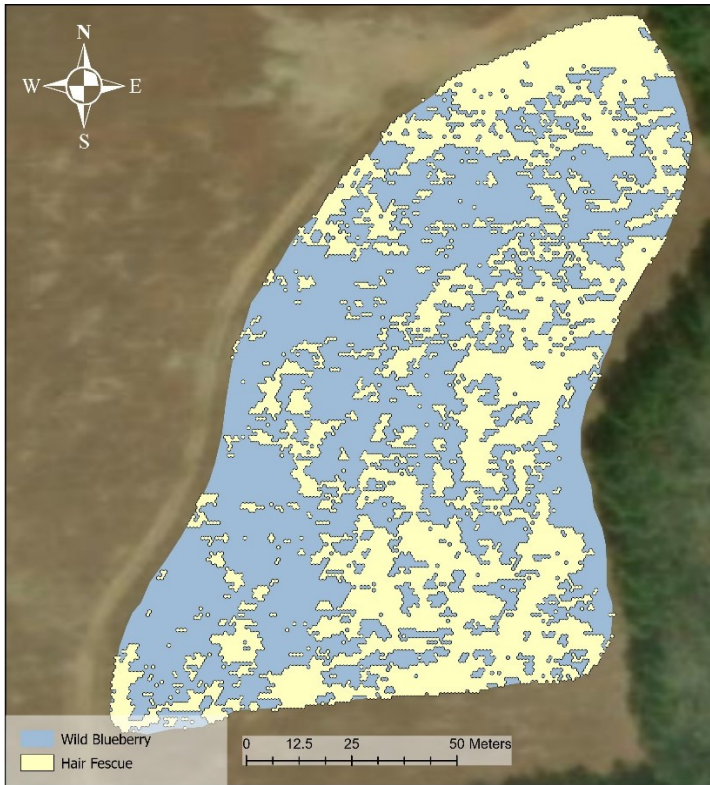
Figure 5-2: Prescription maps for sites 1 (top), 2 (middle) and 3 (bottom) showing wild blueberry non-target areas (blue) and hair fescue target areas (yellow)

Product was applied in site 1 on December 3, 2022, in site 2 on December 15, 2022 and in site 3 on December 16, 2022. Average wind speeds during application were 5.81, 5.36 and

3.13 m s^{-1} during application at each of sites 1, 2 and 3 respectively. Casoron® G4 (dichlobenil) was applied at 7000 g a.i. ha^{-1}. Each plot was 35 m by 7.31 m with a 15 m buffer between adjacent plots. The novel applicator was used in both the spot and broadcast applications as it still maintains its stock functionality. Within each of the test plots, 10, 134 mm by 288 mm, Catchmaster glue traps (AP&G Co., Inc., Bayonne, USA) were placed in target locations as defined by the presence of hair fescue and 10 were placed in non-target locations as defined by a lack of hair fescue. The hypothesis was that when the prescription track was driven, traps placed in target locations would collect applied product while the traps placed in non-target locations would remain free of product.

Following application, all traps were collected, and labeled as either hit or missed in terms of product application. These labels were then compared against their placement (target or non-target locations) to determine the precision, accuracy, sensitivity, and specificity of the novel applicator. Precision considers when the applicator is applying product and how often that is in the correct location. It is determined using equation 5-1

$$Precision = \frac{TP}{(TP + FP)}$$

Eq. 5-1

where, TP is the number of true positives and FP is the number of false positives. Accuracy considers how often the applicator is applying product in target areas as well as how often it is not applying product in non-target areas. It is determined using equation 5-2

$$Accuracy = \frac{TP + TN}{(TP + TN + FN + FP)}$$

Eq. 5-2

where, TN is the number of true negatives and FN is the number of false negatives. Sensitivity considers how often the applicator applies product in target areas. It is determined using equation 5-3.

$$Sensitivity = \frac{TP}{(TP + FN)}$$

<div align="right">Eq. 5-3</div>

Specificity considers how often the applicator is not applying product in non-target areas. It is determined using equation 5-4.

$$Specificity = \frac{TN}{(TN + FP)}$$

<div align="right">Eq. 5-4</div>

Hair fescue vegetative tuft data was likewise collected from each plot before and after application. To do this, a tape measure was laid between both sets of diagonal corners of each plot. After selecting a random starting point using a random number table, 10 samples were taken at equal distances from one another along each of the lines. At each sampling point a 0.5 m x 0.5 m quadrat was placed and all living and non-living tufts were counted. Tufts were considered living if even a single green leaf were found on the plant. Living tuft counts before application were collected on December 1, 2022 in sites 1 and 2 and on December 2, 2022 in site 3. Living tufts after application were counted on May 26, 2023 in site 2 and on May 24, 2023 in site 3. Data for site 1 was not reliable after application as the field owner sprayed the contact herbicide glufosinate ammonium (Ignite® SN) in the spring prior to counting. Glufosinate causes necrosis of green plant tissue and thus made living (e.g., green) tuft counts impossible. For this reason, living tuft data from site 1 was omitted from the analysis.

5.4 Results and Discussion

Performance data from the in-field evaluation is presented in Table 5-1. These data were calculated based on positive and negative glue trap targets (Figure 5-3).

Table 5-1: Performance data from field evaluation of applicator based on the collection of applied granules in both target and non-target locations

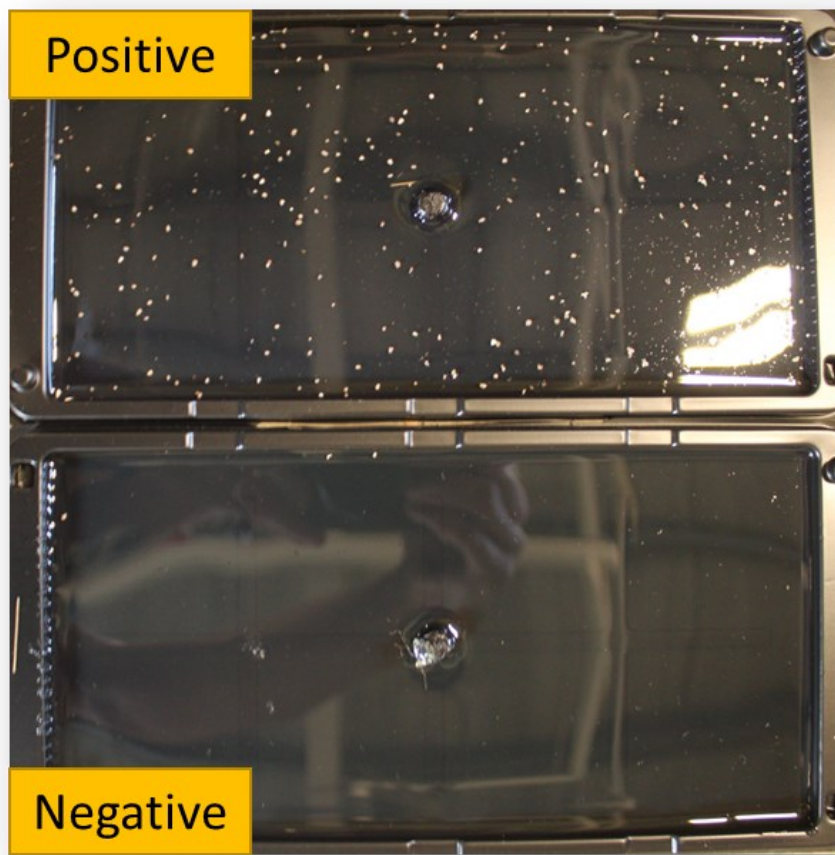| Metric	Percentage (%)
Accuracy	95
Precision	91
Sensitivity	99
Specificity	91

Figure 5-3: Example of glue traps with applied Casoron® G4 (top) and glue traps which did not have Casoron® G4 applied (bottom)

Accuracy, precision, sensitivity, and specificity were all > 90% (Table 5-1). The applicator's measured accuracy of 95% is quite encouraging as this metric best

encapsulates the overall system performance. While 95% is encouraging, it is important to consider the other calculated metrics as they lend a better understanding of where the systems shortcomings are and how it might be further improved.

The calculated sensitivity of 99% suggests that the system was highly adept at applying product in target locations. Comparatively, the specificity of 91% suggest that the system has a slight tendency to overapply product in non-target areas. That said, for the application of herbicides, high sensitivity is more important than high specificity as the main goal is ensuring that all weeds are targeted. The most likely cause for the lower specificity is the buffer zones which were incorporated around the target areas during the generation of the prescription map. This method is described in Bilodeau et al., 2023, and was done for several reasons. First, the buffer zones ensure that weeds were targeted correctly independent of any slight GNSS inaccuracies. Second, buffer zones help to account for seeds spread via primary seed dispersal and their resultant seedlings, which were too small to be identified via the aerial imagery. Finally, the buffer zones act as a sort of blurring effect during map generation which dramatically reduces the complexity and file size of the maps and improves the in-field processing time. This all results in a scenario where management zones, as defined by the prescription map, can fall between two orifices and both orifices were therefore turned on. This meant that a small amount of product was applied outside of target areas as the application width for a single orifice is 0.61 m. It should also be noted that the minimum polygon size used in the maps was a 0.25 m^2 regular hexagons. This meant that if a single hexagon was present in the map, even a single orifice would overapply on both sides of the target area due to the minimum application resolution of 0.61 m. The systems specificity could be improved by shrinking or removing these

buffer zones however, this would likely come at the cost of decreasing the sensitivity. Another way to consider the system performance is through precision. With a precision of 91% the system performed well. As with specificity, precision could be increased in the system though this would come at the cost of decreasing the sensitivity. In all, the high sensitivity at the cost of slightly reduced precision and specificity is the ideal balance for targeting hair fescue and therefore this design was deemed successful.

While the potential for the system to apply product in the correct locations was encouraging, it was likewise important to assess the potential of spot applied Casoron$^®$ G4 for controlling hair fescue, when applied spot specifically using the applicator. There was a significant interaction between site and treatment (p = 0.003) and therefore data were analyzed on separately across sites. There was no significant difference in terms of within site initial tuft density (p < 0.001, for both sites). Average initial tuft densities were 22.24 tufts m^{-2} and 39.00 tufts m^{-2} for sites 2 and 3 respectively.

Table 5-2: Hair fescue living tuft density (tufts m^{-2}) measured in Spring 2023 following Casoron$^®$ G4 application in Fall of 2022 in blueberry fields located in Murray Siding (Site 2) and Kemptown (Site 3) Nova Scotia.

	Site 2 (living tufts m^{-2})	Site 3 (living tufts m^{-2})
Control	25.48a	44.80a
Broadcast Application	5.32b	9.00b
Spot Application	5.28b	9.40b

Means within a column followed by the same letter are not significantly different according to Fisher's LSD (P≤0.05)

Broadcast and spot applications of dichlobenil gave equivalent reductions in hair fescue living tuft density relative to the nontreated control at each site (Table 5-2). Dichlobenil was therefore once again effective on hair fescue, and the results demonstrate that spot applications can be made with the novel applicator without compromising weed

control. This result is highly encouraging as it represents the potential for significant product and cost savings when applying Casoron® G4. When mapping the sites, target areas (as denoted by the presence of hair fescue) accounted for 33.89% of the total area on average. Considering the cost of Casoron® G4 is \$1873.00 ha^{-1}, the system theoretically saves \$1238.24 ha^{-1} before accounting for any supplemental costs or savings associated with the system or its operation. It is also important to note that despite the systems accuracy of 95%, there was not a significant reduction in the degree of hair fescue treatment.

This trial demonstrates the first successful development of a precision spot applicator in any cropping system. While it was designed with wild blueberry in mind, other cropping systems could benefit from this technology. Cranberry (*Vaccinium macrocarpon*) is an excellent candidate as dichlobenil is also widely used in cranberry for controlling a variety of perennial grasses, broadleaf weeds and sedges (Demoranville & Devlin, 1969; Sandler, 2010; Sandler et al., 2004). It can be applied mechanically using tractor driven drop spreaders though; it is often applied manually and spot specifically due to the high costs of the herbicide (Sandler, 2013; Swinkels, personal communication). By developing an appropriate prescription map of the target weed, similar performance to what was seen in this trial should be achievable regardless of the crop. Further, the functional components of the system are not inherent to the Valmar 1255 TR and could easily be adapted to work with any air boom spreader configuration. For this reason, the systems implementation in row crops using different applicators is not beyond the realm of possibility. Future research would be needed to assess which crops specifically could

benefit from spot application of granular agrochemical and how the system could be implemented.

In addition to dichlobenil, the applicator could see use with other granular herbicides such as trifluralin (Bonanza® 10G, Rival 10G, Treflan® TR-10), a group 3 herbicide which is used in a variety of field crops for controlling grasses and broadleaf weeds (Loveland Products Canada, 2011). Alternatively, granular insecticides such as tefluthrin (Force® 6.5G), bifenthrin (Bifen L/P) and chloropyrifos (Saurus®) could benefit from the developed technology if the appropriate use cases are identified. Further work is needed to identify these implementations.

5.5 Conclusions

The field assessment carried out in this study clearly demonstrated the potential of the developed applicator as spot applications of dichlobenil with the applicator were equivalent in efficacy to broadcast applications. With a sensitivity of 99%, it was clear that the system was able to target hair fescue patches within wild blueberry fields based on inputs from a prescription map. The overall accuracy of 95% demonstrated a slight propensity to overapply product which, given the nature of herbicide applications, is the preferable side to error on. While it is certain that the system has the potential to save growers money, future studies should look at a full economic assessment of the system to properly quantify its potential benefit and payback.

5.6   References

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CHAPTER 6: ECONOMIC EVALUATION OF A NOVEL PRECISION APPLICATOR FOR DICHLOBENIL APPLICATION

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6.1   Abstract

This study was an economic assessment of a recently developed spot applicator for granular agrochemicals. The scenario developed in this analysis looked at applying Casoron® G4 (dichlobenil) on hair fescue in wild blueberry. From a temporal perspective, the spot applicator was able to reduce application time by 31.6% compared with broadcast application. This was due largely to needing fewer product refills. In terms of cost savings, the applicator reduced per hectare application costs by $1184.12 (63%). Based on the cost to upgrade to the applicator the payback breakeven point was 47.58 ha if the user required the purchase of all equipment. If the user already owned an applicator, GPS, rate controller and swath control, then this figure was reduced to 4.47 ha. While the system was unable to reduce costs to the point of industry standard Kerb™ SC (pronamide), it does provide a cost-effective alternative to aid in resistance management. While the applicator

was specifically developed for use in wild blueberry, it has potential for application in other cropping systems, particularly cranberry. Future work and analyses should explore these alternate cropping systems.

6.2   Introduction

It is well established that spot application of agrochemical is an effective means of cost reduction when applying pesticides (Tona et al., 2018). While spot sprayers are increasingly popular, there has been no significant progress made towards spot application of granular agrochemical before this project. Chapters 4 and 5 discussed the development of a novel precision spot applicator and the realization of the world's first mechanized system to this purpose. The developed system had an application accuracy, precision, sensitivity, and specificity of 95%, 91%, 99% and 91% respectively. With system performance at an encouraging level, it is important to develop an understanding of how the system impacts growers from an economic standpoint. As wild blueberry was the basis for the development of this applicator, this is where the focus of the analysis will lie. That said, if economically feasible, the system has potential in a variety of cropping systems.

Wild blueberry is Canada's most valuable fruit export with a 2022 export value of over \$366 million. This represents 32.6% of all fruit exported by the country (Statistics Canada, 2023). Despite the value of the commodity, wild blueberry production faces significant challenges in the form of perennial weed pressure. Wild blueberry fields are not tilled each year and therefore, perennial weeds play a critical role in the success of the crop. The weed of greatest concern to the industry is hair fescue (*Festuca filiformis)* (Wild Blueberry Producer's Association of Nova Scotia, 2022) which, causes yield losses of over 50% (White, 2019; Zhang, 2017; Zhang et al., 2018). In Nova Scotia, hair fescue has

rapidly spread since 2001 when it was found in only 7% of fields to now having a presence in over 75% of fields throughout the province (Lyu et al., 2021). Conventional management of this weed has relied almost entirely on pronamide, a group 3 herbicide which provides > 90% hair fescue control (White, 2019; Zhang et al., 2018). While hair fescue resistance to pronamide has not been noted in literature, similar turfgrasses such as annual bluegrass (*Poa annua*) have evolved resistance after routine use of pronamide (McCullough et al., 2017). This overreliance on a single herbicide could lead to selection for herbicide resistance and necessitates the need to find alternative herbicide solutions.

Dichlobenil (Casoron® G4) is a group 29 herbicide which is used to control a variety of grasses, sedges, and broadleaf weeds. While it is registered for use in wild blueberry, it has seen limited implementation due to its high product cost of over $1800 ha^{-1} (Truro Agromart, 2023). Results from chapters 2 and 3 demonstrate similar efficacy of pronamide (2240 g a.i. ha^{-1}) and dichlobenil (7000 g a.i. ha^{-1}) on hair fescue. The results likewise demonstrated a significant increase in wild blueberry yield in plots applied with dichlobenil (7000 g a.i. ha^{-1}) compared with those which applied pronamide (2240 g a.i. ha^{-1}). In combination, these results justify the use of dichlobenil in wild blueberry however, the elevated cost remains a challenge for growers.

Given 1) the wild blueberry industry's significant challenges related to hair fescue management, 2) wild blueberry grower's overreliance on pronamide for managing hair fescue 3) the demonstrated potential of granular dichlobenil to control hair fescue in wild blueberry and 4) the recent development and success of a novel precision spot applicator for granular agrochemical; the goal of this study was to asses the economic impact of the

applicator and how it could challenge the conventional approach to hair fescue management in wild blueberry.

6.3   Materials and Methods

The novel applicator can be considered as an upgrade package for an existing air boom spreader. This package does come at a cost to growers however, the costs are recuperated in the form of agrochemical savings. By assessing how long it takes to recuperate this investment, growers can better understand the potential impact of the system. To this end, payback period was included as the primary metric in this analysis. Payback period was calculated using equation 6-1, where P is the payback period, C is the investment cost and S is the total money the system would save for a given time or applied area. A breakdown of the investment costs can be seen in Appendix 6-1.

$$P = \frac{C_i}{S}$$ Eq. 6-1

Three unique costing scenarios were analyzed in this study and are summarized in Table 6-1.

Table 6-1: Three costing scenarios based on which equipment needs to be purchased prior to employing the novel spot applicator

Startup Options	Condition
Setup 1	Requires purchase of all equipment
Setup 2	Already owns John Deere rate controller, receiver, monitor and swath control
Setup 3	Already owns Valmar 1255 TR, John Deere rate controller, receiver, monitor and swath control

For each of the scenarios defined in Table 6-1, payback periods were calculated for 10, 50 and 250 applied ha per year. In all analyses, the following assumptions were used.

First, herbicide would be applied once every two years per best management practices. Travel speed of all application systems would be 1.34 m s^{-1}. Per hectare cost of Casoron$^®$ G4 and Kerb™ SC would be \$1873.00 and \$435.00 respectively (Esau et al., 2019; Perennia, 2019; Truro Agromart, 2023). Application rate for mixed Kerb™ SC was 500 L ha^{-1} while Casoron$^®$ G4 application rate was 175 kg ha^{-1}. These values were based off the recommendation provided by Perennia (Perennia, 2019). Fuel consumption was estimated at 22 L hr^{-1} (TractorData, 2012) and price of diesel was \$1.55 L^{-1}. Refill time, including fuel and agrochemical, for both the applicator and the sprayer was estimated at 30 minutes (Esau et al., 2016). During refill time, fuel consumption was estimated at 4.3 L hr^{-1} (Molari et al., 2019). For Kerb™ SC, this time accounts for driving back to the refill area, putting on the required safety gear, measuring the herbicide, triple rinsing the bottles, mixing the herbicide, and returning to the application area. For Casoron$^®$ G4 this includes, driving back to the refill area, putting on the required safety gear, opening and dumping each of the 15 bags required to fill the hopper, disposing of the empty bags, and returning to the application area. It should be noted that Casoron$^®$ G4 is not routinely sold in bulk in Nova Scotia. The refill time could be reduced significantly if this were the case. Sprayer booms were 13.7 m and 7.32 m while the applicator boom was 7.32 m. The 13.7 m sprayer tank volume was 1135 L, the 7.32 m sprayer tank volume was 946 L and the applicator hopper volume was 509 L. Sprayer boom sizes were selected as they are good representations of equipment Nova Scotian wild blueberry growers already own. Setup time for drone flights was estimated at 20 minutes. Drone flight time was averaged between the three fields at 208 s ha^{-1}. Parameters for the drone flight can be seen in Appendix 6-2. Average fescue coverage was 33.89% as determined by analyzing the aerial images from three field sites

located in Nova Scotia's Colchester County. Sites 1 (45.364875, -63.213123) and 2 (45.369061, -63.206695) are located in Murray Siding while site 3 (45.500496, -63.102192) is located in Kemptown. The three sites in order were 1.96, 1.33 and 3.00 ha. Fescue was detected from the imagery using the methods detailed in (Bilodeau et al., 2023). Product overapplication was calculated at 8%. All other maintenance and operational costs were held constant between scenarios.

Application time and cost were likewise calculated for each of the scenarios. Application cost was calculated using equation 6-2 for broadcast applications and equation 6-3 for spot applications.

$$t_{app} = \left(\frac{A_{farm}}{w * v}\right) + t_{refill}\left(\frac{A_{farm}}{A_{tank}}\right) \qquad \text{Eq. 6-2}$$

$$t_{app} = \left(\frac{A_{farm}}{w * v}\right) + t_{refill}\left(\frac{A_{farm}}{A_{tank}}\right) + t_{drone} \qquad \text{Eq. 6-3}$$

In equation 6-2 and 6-3, t_{app} is the application time, A_{farm} is the area of the farm, w is the width of the applicator/sprayer boom, v is the travel speed of the equipment, t_{refill} is the time to refill the tank/hopper, A_{tank} is the area that a full single tank/hopper can cover at the target application rate and t_{drone} is the time required to setup and fly the drone for prescription map development. Uptime was also a key metric used in analyzing the systems. It is expressed as the percentage of time the system is actively applying product compared with the total time required to apply the product including refilling. Application cost was calculated using equation 6-4.

$$C_{app} = \left(A_{farm} * C_{ha}\right) + \left(t_{app} * F_c * P_{fuel}\right) \qquad \text{Eq. 6-4}$$

In equation 6-4, C_{ha} is the cost of the herbicide per hectare, F_c is the fuel consumption of the tractor and P_{fuel} is the price of fuel. All other defined parameters were consistent with previous equations.

6.4   Results and Discussion

The first step in the analysis was to determine the application time required for each of the scenario combinations. Results of these calculations are summarized in Table 6-2.

Table 6-2: Calculated application time for each application condition and farm sizes and uptime for each implement

	Application Time by Farm Size (hours)			
	10 ha	50 ha	250 ha	Uptime (%)
7.32 m Broadcast Applicator	5.44	27.18	135.9	52.09
7.32 m Broadcast Sprayer	5.48	27.39	136.94	51.70
13.7 m Broadcast Sprayer	3.72	18.58	92.89	40.72
7.32 m Spot Applicator	3.72	18.58	92.88	76.22
7.32 m Spot Sprayer	3.73	18.64	93.2	75.96
13.7 m Spot Sprayer	2.26	11.3	56.48	66.97

As would be expected, the data demonstrates the potential time savings of a larger boom and tank size with the 13.7 m applicator having the shortest application time while spot spraying also had a considerable effect on application time. The primary factor contributing to spot applications greater uptime, is that reduced product usage requires less time to refill the hopper/tank during applications. Further, the requirement to setup for drone flights and map the fields is still more efficient from a temporal perspective given the time savings associated with needing less refills during spot applications. Uptime for each of the implement combinations can be seen in.

Interestingly, despite having the lowest total application time, the 13.7m sprayer was the least efficient in terms of uptime. This result demonstrates the value of the larger boom and how a greater proportion of time is spent refilling the tank compared with the smaller sprayer and applicator. Both the 7.32 m applicator and sprayer showed very little difference in application time or uptime. In terms of applied hectarage per tank/hopper, spot application covers 295% of the hectarage achievable with broadcast application in this scenario. The key conclusion from the temporal data is that for the same size boom, the applicator is no less efficient than the sprayer from a time perspective, though it is likely that a wider boom would make the applicator even more efficient.

While the time savings with spot application are encouraging, ultimately, adoption of the technology will rely largely on cost savings. Application costs for each of the farm sizes and equipment combinations are provided in Table 6-3.

Table 6-3: Cost of product application for each of the application conditions and farm size combinations

Configuration	Farm Size		
	10 ha	50 ha	250 ha
7.32 m Broadcast Applicator	$18,932.73	$94,663.64	$473,318.19
7.32 m Broadcast Sprayer	$4,554.41	$22,772.06	$113,860.31
13.7 m Broadcast Sprayer	$4,491.39	$22,456.94	$112.284.70
7.32 m Spot Applicator	$7,090.82	$35,454.10	$177,270.51
7.32 m Spot Sprayer	$1,795.16	$8,975.80	$44,879.00
13.7 m Spot Sprayer	$1,734.09	$8,670.44	$43,352.22

The analysis shows that at typical application rates, Casoron® G4 is far more expensive than Kerb™ SC. While this was already well established, confirmation demonstrates why Casoron® G4 has seen little implementation in wild blueberry and the need to find cost mitigating strategies if this product is to see widespread implementation. The results from Chapters 3 and 5 demonstrate the practical success of spot applied

Casoron® G4 and its similarity in treatment effectiveness to broadcast applications. Table 6-3 demonstrates the significant cost savings that spot application represents. In combination the results show that spot application reduced Casoron® G4 application costs by 62.5%. This figure is largely based on hair fescue coverage which was set at 33.89% in this analysis. As an example, if the coverage were reduced to 10%, spot application of Casoron® G4 would reduce application costs by 88.3%. This demonstrates the increasing benefits of spot application as the target area decreases. Even when spot applied in this scenario, Casoron® G4 remains more expensive than broadcast Kerb™ SC. While this is not ideal, the lack of alternative products to manage hair fescue (White, 2018b; White & Zhang, 2020) and the risk of Kerb™ SC selecting for herbicide resistance should justify the use of Casoron® G4. Ultimately, success will be based on cost, and spot application with the developed applicator demonstrates the potential to reduce the application cost significantly.

After considering the cost savings, the next step in the analysis was to determine how quickly growers could recuperate the investment cost of purchasing or upgrading to the spot applicator. Factors contributing to the cost of the applicator are listed in Appendix 6-1. Payback periods for each of the costing scenarios are outlined in Table 6-4. Note that this analysis accounted for the fact that fall applied herbicides for managing hair fescue are only applied every two years prior to wild blueberry stem emergence.

Table 6-4: Payback period for each of the costing scenarios and farm size combinations in years

Setup	Payback in Years		
	10 ha	50 ha	250 ha
Setup 1	9.52	1.90	0.38
Setup 2	4.36	0.87	0.17
Setup 3	0.89	0.18	0.04

*Setup 1 assumes the purchase of all components is required. Setup 2 assumes the grower already owns a rate controller, GPS receiver, monitor and swath control. Setup 3 assumes the grower already owns a boom applicator, rate controller, GPS receiver, monitor and swath control

Even in the worst case, where a grower needs to purchase all the equipment and upgrades, and are only farming 10 ha, they can recuperate their investment in less than 10 years. For each of the setups, the 250 ha farm is able to recuperate the investment within the first year. Breakeven points for each of the setups are 47.58 ha, 21.80 ha, and 4.47 ha for each of setup 1, 2, and 3 respectively. This is highly encouraging as for most medium and large sized operations, the cost of upgrading to the spot applicator is marginal based on the return. It should be noted that the cost breakdown for the developed applicator is for the prototype discussed in Chapters 4 and 5. Future development of the applicator would look at more robust materials for the valve and a simplification of the control system with printed circuit boards. This would influence the cost, though it isn't anticipated that it would alter the conclusions about the payback, as the herbicide cost savings would still far outweigh any additional material costs.

In this analysis, a maximum label application rate of 175 kg ha^{-1} (7000 g a.i. ha^{-1}) was used for Casoron® G4. Cranberries (*Vaccinium macrocarpon*), a crop which frequently utilizes Casoron® G4 for weed management has a maximum label rate of 112.5 kg ha^{-1} (4500 g a.i. ha^{-1}) and has documented and recommended uses as low as 56.25 kg ha^{-1} (2250 g a.i. ha^{-1}). Casoron® G4 is most commonly used in cranberry for controlling swap dodder

(*Cuscuta gronovii*) an economically destructive parasitic weed shown to reduce yields by 80 to 100% (Bewick et al., 1989; Dawson, 1970; Hunsberger et al., 2006; Sandler, 2013). Taking an average of the documented high and low application rates returns 84.38 kg ha^{-1}. This would result in a uniform application cost of $903.20 ha^{-1}. Using Hunsberger et al., 2006 as a basis, average swamp dodder coverage can be estimated between 44% and 66% in their sampled fields. Using 55% as a basis would reduce application costs from $9234.73 to $5590.82 on a 10 ha field. While this figure is not as influential as the wild blueberry example, it still results in breakeven points of 154.97 ha, 71.01 ha and 14.57 ha for each of the costing scenarios outlined in Table 6-1. It should be noted that Hunsberger et al., 2006 selected sites with known, uniform and previously undisturbed swamp dodder infestations. Therefore the 55% coverage represents a worst-case scenario with lesser infestations resulting in greater profitability. Further, use in cranberry would be dependent on the ability to adequately map swamp dodder infestation from aerial imagery which has yet to be explored by literature. With this said, many cranberry growers are still relying on manual Casoron® G4 applications (Swinkels, personnal communication).

Beyond wild blueberries and cranberries, the applicator could see use in any crops which employ dichlobenil. Blackberry (*Rubus* spp.), raspberry (*Rubus* spp.) , apple (*Malus* spp.), pear (*Pyrus* spp.), cherry (*Prunus* spp.), grapes (*Vitis* spp.), ornamental flowers, and various municipal uses are all areas which see implementation of dichlobenil for controlling weeds (United States Environmental Protection Agency, 1998). While the specific configuration of the applicator may need to be adapted for these crops, the concept would remain the same, and the potential for significant cost savings is encouraging.

In addition to other crops, the cost benefit of the novel applicator could be improved by implementing it for control of other weeds in wild blueberry. Significant reductions in red sorrel (*Rumex acetosella* L.) ramet and seedling density have been demonstrated using dichlobenil (White et al., 2020). As red sorrel is the most abundant weed found in Nova Scotian wild blueberry fields (Lyu et al., 2021), there is considerable potential to implement dichlobenil and the developed applicator to aid in managing this economically destructive weed. Dichlobenil has likewise shown some success in controlling other problematic weeds in wild blueberry such as hawkweed (*Hieracium caespitosum* Dumort) and quack grass (*Elymus repens*)(Eriavbe, 2015; Hertz, 1970). Despite this, there is more work required to determine the full spectrum of possible uses for dichlobenil in wild blueberry. With more research, there may come further implementations and cost saving potential for the applicator.

6.5   Conclusions

In all, the developed applicator was highly successful as a means of cost and application time reduction compared with conventional broadcast applications. Given wild blueberry's particular challenge with hair fescue and the need to find alternative solutions for resistance management, the results demonstrate the applicators potential to address these concerns from an economic viability standpoint. While spot application of Casoron® G4 was still more expensive than Kerb™ SC, the goal was never to replace Kerb™ SC. Best resistance management practices should see a combination of both products used to prolong the benefits of each product. The developed applicator makes this more feasible from a cost perspective by reducing the per hectare costs by 62.5%. This, combined with a breakeven application area of 47.58 ha if all equipment had to be purchased, should serve

as significant justification for the adoption of this technology. Future work could explore

the economic potential of the applicator in other cropping systems, in particular cranberry.

6.6 References

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6.7   Appendix

Appendix 6-1: Summary of investment costs associated with the novel spot applicator

Parts	Unit Price	Units	Total
Bistable Rotary Solenoids	165.68	12	$1,988.16
3D Printing Time ($/hr)	2.27	102	$231.54
3D Printing Material ($/g)	0.05	1224	$61.20
Spiral Flex Hose ($/m)	5.25	50	$262.50
Blower Fan Pulley	11.99	1	$11.99
Zip Ties (per 100)	16.99	0.24	$4.08
024 Hose Clamps	2.49	24	$59.76
Hydraulic Hose Extension	65.57	1	$65.57
½" Steel Pipe	15.99	1	$15.99
18-gauge Steel Sheet	10.5	1	$10.50
Motor Driver	68.95	6	$413.70
Arduino UNO	35.99	6	$215.94
DC-DC Boost Converter	995	1	$995.00
Expansion Board	5.85	6	$35.10
Voltage Regulator	25.53	6	$153.18
60A Circuit Breaker	15.09	1	$15.09
Waterproof Enclosure	352.8	1	$352.80
4 AWG Wire ($/m)	5.64	12	$67.68
14 AWG 2-wire ($/m)	4.85	3	$14.55
18 AWG 2-wire ($/m)	2.43	37.3	$90.64
18 AWG Single ($/m)	1.44	9	$12.96
18 AWG 15-wire	20	8	$160.00
Automotive Fuses	0.39	24	$9.36
47-pin Connector	35.76	1	$35.76
Pins	0.78	13	$10.14
John Deere RC 2000	3400	1	$3,400.00
John Deere Starfire 6000	4500	1	$4,500.00
John Deere Gen 4 Display	11500	1	$11,500.00
John Deere Swath Control	1100	1	$1,100.00
Valmar 1255 TR	30500	1	$30,500.00
Total			$56,293.19

Appendix 6-2: Drone parameters for the development of prescription maps used in analyses

Drone	DJI M300 RTK
Camera	MicaSense Altum
Flight Altitude	91 m
Front Overlap	80%
Side Overlap	70%
Flight Speed	16 m s-1
GNSS	GPS + GLONASS + BeiDou + Galileo

CHAPTER 7: CONCLUSIONS

This thesis aimed to address five specific objectives. Objective one was to assess the effect of dichlobenil for hair fescue management at varying application rates in Nova Scotian wild blueberry fields. Three different dichlobenil application rates were explored (4400, 5700 and 7000 g a.i. ha^{-1}) and compared with industry standard pronamide (2240 g a.i. ha^{-1}). Dichlobenil rates had a significant effect on hair fescue vegetative tuft density, flowering tuft density, and mean inflorescence number at all rates when compared with the control. The high rate of dichlobenil was not significantly different from pronamide in terms of these same variables. The high rate of dichlobenil was the only treatment which resulted in significantly greater wild blueberry yield than the control. Generally, it can be concluded that all tested application rates of dichlobenil are an improvement on the control. Overall, the high rate performed the best and given that it demonstrated limited differences to the widely used pronamide, dichlobenil represents a great alternative product for growers to employ. Given that high rate dichlobenil trials likewise produced greater wild blueberry yields seems to indicate that dichlobenil may have less of a detrimental effect on the wild blueberry plants themselves. More research would be needed to confirm this hypothesis.

The second objective was to assess the effect of spot applied dichlobenil for hair fescue management in Nova Scotian wild blueberry fields. Spot and broadcast applied dichlobenil at 7000 g a.i. ha^{-1} were compared with pronamide at 2240 g a.i. ha^{-1}. Dichlobenil had a significant effect on hair fescue vegetative tuft density, flowering tuft density, and mean inflorescence number whether spot or broadcast applied when compared with the control. For the same parameters there were limited differences observed between dichlobenil applications and pronamide. Further there were no significant differences

between any of the treatments in terms of wild blueberry yield. These results support the development of a precision spot applicator as a means of reducing the significant cost of broadcast dichlobenil application. Based on the results of this trial, spot application of dichlobenil is comparable to broadcast pronamide though the need to introduce a buffer around tufts should be considered. Such a buffer would reduce the potential for future seedling recruitment given the product can only be applied every two years.

The third objective was to modify an air boom spreader to accommodate spot application of granular agrochemical. This development modified a Valmar 1255 TR by altering several critical facets. First, the gearing ratio between the gas motor and blower fan was adjusted to increase the volumetric airflow within the hoses. A second set of hoses were then added between the boom orifices and the hopper to return unused product back to the applicator. Custom control valves were designed and mounted immediately before each of the boom orifices. The valves were controlled using a predeveloped prescription map, a rate controller and a custom developed control box. In all, the system was able to take a positive hair fescue detection from a prescription map, move product out to the boom orifices, make the decision to apply or recycle product and return unused product to the hopper all while eliminating product degradation. In lab evaluating the system, there were zero instances where the valves jammed and zero instances where the valves were in the incorrect position based on the signal from the prescription map. While at this stage, the system still needed field evaluation, the overall design serves as a promising prototype and confirmed the potential to recycle and redirect Casoron® G4 effectively.

The fourth objective was to field evaluate the developed applicator based on accuracy, precision, sensitivity, and specificity as well as its ability to manage hair fescue

in both spot and broadcast configurations. By placing glue traps in both target and non-target locations the above-mentioned parameters could be calculated based on the presence or lack of herbicide granules collected on the traps. The overall system accuracy was calculated at 95%. The majority of the 5% error was attributed to a slight tendency to overapply product as demonstrated by the 91% specificity and 99% sensitivity. That said, this sensitivity to specificity ratio is in the optimal range given the intended use of the system. While the specificity of the system could be increased it would come at the cost of the sensitivity. The sensitivity is the more important metric however, as it demonstrates how often herbicide is applied to hair fescue tufts. A slight amount of over application is justifiable as it is needed as a buffer to reduce the possibility of seedling recruitment nearby established tufts. Further, the minimum resolution of the applicator is 0.61 m while the maps used a resolution on 0.25 m. This difference creates a small amount of allowable overapplication. Finally, the precision of the system was 91%. Again, this serves as confirmation of the systems slight propensity to overapply product. In all the systems performance was highly encouraging and represents the world's first successful development of a granular spot applicator.

The final objective was to quantify the economic potential of spot applied dichlobenil as compared to uniform application and traditional management strategies. While the applicator was not able to reduce Casoron® G4 costs to the same level as Kerb™ SC, it did significantly reduce the costs when compared with its own broadcast application. Per hectare costs were reduced by 62.5%. If all equipment including the stock applicator had to be purchased, the initial investment could be recuperated in product savings in 47.58 ha. If the operator only needs to purchase the upgrades, the system would pay itself off in

4.47 ha. Both figures are relatively small given the large hectarages most growers will be managing. Further, with a more cost-effective means of applying Casoron® G4, growers will be more inclined to include it in their management strategies and aid in the resistance management concerns associated with pronamide usage. This will have the benefit of prolonging the effective lifespan for both pronamide and dichlobenil without compromising treatment efficacy.

Each of the objectives of this study were met and produced results which will be highly beneficial to the Nova Scotian wild blueberry industry. Further, the development of the applicator could have farther reaching effects in cropping systems beyond wild blueberry if the appropriate uses can be identified. Cranberries are the obvious implementation given the current use of dichlobenil in that crop, but other crops may benefit from spot fertilizer, insecticide, or other granular herbicides. Further research would be needed to identify and test these implementations. As for dichlobenil itself, confirmation of its effectiveness versus hair fescue provides growers with an alternative to pronamide which will help in combatting herbicide resistances without compromising on treatment effectiveness. Even with the success of the spot applicator, further approaches should be explored to aid in reducing dichlobenil application cost. Finally, future work on the applicator should aim to make the components more robust to ensure system longevity while working to simplify and reduce the footprint of the control system through a printed circuit board approach.

7.1   Future Considerations

The conclusions of this thesis present several key findings which could serve as important areas for future research. First, while the efficacy of dichlobenil to control hair

fescue was clearly demonstrated, its price point, even when spot applied, may still be too high for many wild blueberry growers with more serious hair fescue infestations. For this reason, research should continue to explore alternative herbicide formulations to find products which can support pronamide's demonstrated efficacy at an effective price point.

Second, to expand the novel applicator's use cases, other implementations should be explored such as alternate cropping systems or alternate agrochemicals. Cranberry is the evident option given the similarities between the crops and the documented use of dichlobenil. That said, other cropping systems may have use cases for dichlobenil which are not currently employed due to the herbicide's cost. With the development of the novel spot applicator, this may create opportunities for future dichlobenil implementation. Beyond dichlobenil, the applicator should be assessed for its potential to apply a variety of granular agrochemicals such as granular herbicides, insecticides, and fertilizers. Through identifying alternate uses for the system, it may help to make the return on investment more attractive to farmers.

Third, the applicator design requires a few modifications as it is progressed towards commercialization. The current design of the system relies on 3D printed polylactic acid valves. While this approach suffices for prototyping and testing, the long-term durability of the product is not sufficient. Commercialized designs should look at more robust polymers or metals as a means of ensuring the system's integrity over a longer period. Further, the current control system used to actuate the solenoids utilises simple Arduino circuitry and requires a large enclosure to house the components. While system performance was not compromised by this factor, all of the circuitries could be moved to

a smaller printed board, thereby shrinking the overall footprint and making the system more reliable.

Fourth, the current applicator design is reliant on the development of prescription maps to accurately apply product. This approach has the evident shortcoming that is assumes growers have access to a drone and the appropriate software and expertise to develop maps on their own. While the process can be streamlined with autorun functions, it is still a time consuming endeavor which could benefit from a more temporally efficient alternative. A machine vision-based approach makes the most sense as this alternative. The development of a neural network for identifying hair fescue paired with cameras mounted along the boom of the applicator could alter the decision system away from prescription maps and toward a real time decision. This real time solution would cause little alteration in the way in which growers currently employ applicators. They would simply turn on the system and use it with no need for mapping and processing field data.

Finally, with the shifting regulations in Canada around drone applications of agrochemical, a similar study should be carried out to compare the performance of the developed applicator to an applicator drone. Such a comparison should explore both the economic potential of the two systems along with the ability for the applicator drone to provide a similar degree of accuracy and precision of application to the novel applicator.

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