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FURTHERING INDAZIFLAM-BASED MANAGEMENT STRATEGIES OF THREE INVASIVE ANNUAL GRASSES IN NORTHERN UTAH

by

Peter Weston Maughan

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Plant Science

(Weed Science)

Approved:

Corey V. Ransom, Ph.D. Major Professor	Earl Creech, Ph.D. Committee Member
Tom Monaco, Ph.D. Committee Member	D. Richard Cutler, Ph.D. Vice Provost of Graduate Studies

UTAH STATE UNIVERSITY

Logan, Utah

2023

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ABSTRACT

Furthering Indaziflam-Based Management Strategies of Three Invasive Annual Grasses in Northern Utah

by

Peter Weston Maughan, Master of Science

Utah State University, 2023

Major Professor: Dr. Corey V. Ransom
Department: Plants, Soils, and Climate

Indaziflam is an herbicide highly recognized for its potential to effectively control invasive annual grasses; however, recent concerns have developed among wildland managers that indaziflam may lead to long-term detrimental effects on the landscape. This is due to indaziflam long soil persistence and preemergence mode of action. While many studies have been performed, confirming that indaziflam is indeed effective, fewer studies have maintained the duration to accurately determine any long-term effects. The studies in this thesis performed extended environmental analysis on a variety of landscapes post indaziflam application, as well as explore some potentials for revegetation strategies for indaziflam treated areas. Chapters 2 and 3 present data that was collected from both mildly degraded and largely degraded landscapes, for up to 5 years after indaziflam application. Analysis of that data was used to determine changes in ecological metrics such as richness, diversity, evenness, and functional group percent cover. Chapter 4 presents a pair of smaller studies that aimed to determine the effectiveness of multi-entry herbicide applications, herbicide exclusion, and carbon banding as potential tools in revegetating landscapes post indaziflam application. This thesis asserts that indaziflam maintains long-term invasive annual grass suppression with minimal negative impacts to desirable cover, diversity, etc. This research also concluded that seedings into indaziflam-treated soils 18 months after application can lead to successful emergence when coupled with extensive precipitation.

(181 pages)

PUBLIC ABSTRACT

Furthering Indaziflam-Based Management Strategies of Three Invasive Annual Grasses in Northern Utah

Peter Weston Maughan

Indaziflam is an herbicide highly recognized for its potential to effectively control weedy, winter germinating grasses, such as downy brome, as the herbicides prevents seed germination for several years. Unfortunately, most of these studies only capture the first 2-3 years of indaziflam's 3-5 years soil activity. This thesis sought to better understand indaziflam's long-term effects by monitoring both a healthy ecosystem and a degraded ecosystem for up to 5 years after indaziflam application. A secondary study was also conducted to better understand the potential of revegetation via reseeding in indaziflam treated soils. The study concluded that indaziflam very little long-term negative impact on the ecological health of either ecosystem. The study also found potential evidence that a layer of activated carbon applied between seeding and herbicide application can promote healthy plant germination in indaziflam treated soils.

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Peter Weston Maughan

CONTENTS

Page

Abstract iii

Acknowledgments vi

Contents vii

List of tables x

List of figures xiv

Abbreviations xv

Chapter I: A Literature Review Of Select Species, Herbicides, And Environmental Conditions Pertinent To Weed Management In The Intermountain West 1

Introduction 1

Species of Interest 1

Herbicides of Interest 5

Conditions of Interest 9

Research Objectives 10

References 12

Chapter II: Effects Of Indaziflam-Inclusive Herbicide Mixtures On High Plant Diversity Landscapes Multiple Years After Application 24

Abstract 24

Introduction 25

Methods and Materials 27

Study Results 29

Discussion 36

References 41

Data Tables 45

Data Figure 74

Chapter III: Effects Of Indaziflam-Inclusive Herbicide Mixtures On Highly Degraded, Ventenata Infested Ecosystems Multiple Years After Application 75

Abstract 75

Introduction 76

Methods and Materials 78

Study Results 80

Discussion 89

References 95

Data Tables 98

Data Figure 129

Chapter IV: Furthering Seed-Based Revegetation Strategies For Indaziflam-Treated Areas 130

Abstract 130

Introduction 131

Methods and Materials....133

Study Results....137

Discussion....141

References....144

Data Tables....147

Data Figure....159

Chapter V: Summary....160

References....165

LIST OF TABLES

Page

Table 2.1. Treatments applied to control downy brome near Richmond, UT. 45

Table 2.2. Comprehensive list of all desirable species near Richmond, UT. 46

Table 2.3. Comprehensive list of all invasive species near Richmond, UT. 47

Table 2.4. P-values from a 2017 study near Richmond, UT. 48

Table 2.5. P-values from a 2018 study near Richmond, UT. 49

Table 2.6. *Bromus tectorum* cover from a 2017 study near Richmond, UT. 50

Table 2.7. *Bromus tectorum* cover from a 2018 study near Richmond, UT. 51

Table 2.8. *Balsamorhiza hookeri* cover from a 2017 study near Richmond, UT. 52

Table 2.9. *Balsamorhiza hookeri* cover from a 2018 study near Richmond, UT. 53

Table 2.10. *Lomatium grayi* cover from a 2017 study near Richmond, UT. 54

Table 2.11. *Lomatium grayi* cover from a 2018 study near Richmond, UT. 55

Table 2.12. Desirable grass cover from a 2017 study near Richmond, UT. 56

Table 2.13. Desirable grass cover from a 2018 study near Richmond, UT. 57

Table 2.14. *Helianthus annuus* cover from a 2017 study near Richmond, UT. 58

Table 2.15. *Helianthus annuus* cover from a 2018 study near Richmond, UT. 59

Table 2.16. Invasive plant cover from a 2017 study near Richmond, UT. 60

Table 2.17. Invasive plant cover from a 2018 study near Richmond, UT. 61

Table 2.18. Desirable plant cover from a 2017 study near Richmond, UT. 62

Table 2.19. Desirable plant cover from a 2018 study near Richmond, UT........................63

Table 2.20. Total plant richness from a 2017 study near Richmond, UT...........................64

Table 2.21. Invasive plant richness from a 2017 study near Richmond, UT. 65

Table 2.22. Desirable plant richness from a 2017 study near Richmond, UT. 66

Table 2.23. Total plant richness from a 2018 study near Richmond, UT...........................67

Table 2.24. Invasive plant richness from a 2018 study near Richmond, UT. 68

Table 2.25. Desirable plant richness from a 2018 study near Richmond, UT. 69

Table 2.26. Total plant diversity from a 2017 study near Richmond, UT..........................70

Table 2.27. Total plant diversity from a 2018 study near Richmond, UT..........................71

Table 2.28. Total plant evenness from a 2017 study near Richmond, UT. 72

Table 2.29. Total plant evenness from a 2018 study near Richmond, UT. 73

Table 3.1. Treatments applied to control ventenata near Mt. Sterling, UT. 98

Table 3.2. Comprehensive list of all desirable species near Mt. Sterling, UT. 99

Table 3.3. Comprehensive list of all invasive species near Mt. Sterling, UT. 100

Table 3.4. P-values from a 2017 study near Mt. Sterling, UT. 101

Table 3.5. P-values from a 2018 study near Mt. Sterling, UT. 102

Table 3.6. *Ventenata dubia* cover from a 2017 study near Mt. Sterling, UT. 103

Table 3.7. *Ventenata dubia* cover from a 2017 study near Mt. Sterling, UT. 104

Table 3.8. Annual brome cover from a 2017 study near Mt. Sterling, UT.......................105

Table 3.9. Annual brome cover from a 2018 study near Mt. Sterling, UT.......................106

Table 3.10. *Convolvulus arvensis* cover from a 2017 study near Mt. Sterling, UT. 107

Table 3.11. *Convolvulus arvensis* cover from a 2018 study near Mt. Sterling, UT. 108

Table 3.12. *Lomatium grayi* cover from a 2017 study near Mt. Sterling, UT. 109

Table 3.13. *Lomatium grayi* cover from a 2018 study near Mt. Sterling, UT. 110

Table 3.14. *Allium canadense* cover from a 2017 study near Mt. Sterling, UT. 111

Table 3.15. *Allium canadense* cover from a 2018 study near Mt. Sterling, UT. 112

Table 3.16. Desirable grasses cover from a 2017 study near Mt. Sterling, UT. 113

Table 3.17. Desirable grasses cover from a 2018 study near Mt. Sterling, UT. 114

Table 3.18. Invasive plant cover from a 2017 study near Mt. Sterling, UT. 115

Table 3.19. Invasive plant cover from a 2018 study near Mt. Sterling, UT. 116

Table 3.20. Desirable plant cover from a 2017 study near Mt. Sterling, UT. 117

Table 3.21. Desirable plant cover from a 2018 study near Mt. Sterling, UT. 118

Table 3.22. Total plant species richness from a 2017 study near Mt. Sterling, UT. 119

Table 3.23. Invasive plant richness from a 2017 study near Mt. Sterling, UT. 120

Table 3.24. Desirable plant richness from a 2017 study near Mt. Sterling, UT. 121

Table 3.25. Total plant species richness from a 2018 study near Mt. Sterling, UT. 122

Table 3.26. Invasive species richness from a 2018 study near Mt. Sterling, UT. 123

Table 3.27. Desirable species richness from a 2018 study near Mt. Sterling, UT. 124

Table 3.28. Plant species diversity from a 2017 study near Mt. Sterling, UT. 125

Table 3.29. Plant species diversity from a 2018 study near Mt. Sterling, UT.. 126

Table 3.30. Plant species evenness from a 2017 study near Mt. Sterling, UT. 127

Table 3.31. Plant species evenness from a 2018 study near Mt. Sterling, UT. 128

Table 4.1. Treatments applied to explore resseeding strageties near Riverside, UT. 147

Table 4.2. Treatments applied in Jan 2023 to test plant emergence in treated soils 148

Table 4.3. Treatments applied in May 2023 to test plant emergence in treated soils 149

Table 4.4. Germination counts of two grass species from a 2021 study near Richmond, UT. 150

Table 4.5. Germination counts of one grass species and one forb species from a 2021 study near Richmond. UT. 151

Table 4.6. Medusahead and alfalfa injury from a 2021 study near Richmond, UT. 152

Table 4.7. Small burnet counts from a Jan 2023 greenhosue study. 153

Table 4.8. Small burnet counts from a May 2023 greenhouse study. 153

Table 4.9. Siberian wheatgrass counts from a Jan 2023 greenhouse study.....................155

Table 4.10. Siberian wheatgrass counts from a May 2023 greenhouse study.................156

Table 4.11. Biomass and heights from a Jan 2023 greenhouse study.............................157

Table 4.12. Biomass and heights from a May 2023 greenhouse study...........................158

LIST OF FIGURES

Page

Figure 2.1. Precipitation data from a weather station in Richmond, UT. 74

Figure 3.1. Precipitation data from a weather station near Mt Sterling, UT. 129

Figure 4.1. Shortwave solar radiation data from a weather station on USU campus. 159

ABBREVIATIONS

Amino - Aminopyralid

DAT – Days after treatment

Glypho - Glyphosate

HEZ – Herbicide exclusion zone

Imaz – Imazapic

Indaz - Indaziflam

MAT – Months after treatment

MSO – Methylated seed oil

Propoxy - Propoxycarbazone

Rimsulf - Rimsulfuron

USU – Utah State University

CHAPTER I

A Literature Review Of Select Species, Herbicides, And Environmental Conditions Pertinent To Weed Management In The Intermountain West

Introduction

Invasive weeds have invaded millions of acres across the United States, including the Wasatch Mountains and Great Basin biomes (Clark *et al.* 2019, Monaco *et al.* 2005, Rinella *et al.* 2021), disrupting large sections of native ecosystems (Murry *et al.* 2021, Rinella *et al.* 2021). In 2005, estimates for the economic cost of the damages associated with weeds was approximately $30 billion (Pimentel *et al.* 2005), affecting areas such as croplands, pastures, forests, and wildland management areas by affecting fire regimes, biodiversity, soil nutrient cycling, etc. (Schlesinger *et al.* 1996, Smith *et al.* 1999, Vitousek 1992). While weed management approaches can be mechanical, cultural, and biological, many studies over the years have found that the world is increasingly dependent on chemical herbicides for managing and controlling noxious weed infestations (Benbrook 2016, Gianessi 2013, Sebastian *et al.* 2016, Wagner *et al.* 2017). The purpose of this review will be to briefly describe the biological and ecological concerns that arise from invasive annual grasses in Utah, and present the herbicides commonly used for invasive annual grass management across Utah.

Species of Interest

Constant pressure from drought and fires has created to perfect habitat for invasive winter annual grasses, which altruistically sacrifice themselves as fuel to ignite the western rangelands, clearing the landscape of competitive native species, and providing safe sites for their fast germinating and highly aggressive offspring (Davies *et al.* 2021, McGlone *et al.* 2009, McGranahan and Wonkka 2022, Pilliod *et al.* 2017).

Downy brome *(Bromus tectorum),* also commonly known as cheatgrass or downy chess (Hickmann 1993), is a winter annual grass that likely originated in the Middle East, its weedy nature allowing it to thrive in the constantly disturbed soils of agricultural communities. From there, the grass kept to the shadows of civilization, moving northward into the European continent (Young *et al.* 1987). While early reports show downy brome entering the United States around the 1890's, other reports conclude that the invasive grass was present as early as the 1860's (Mack 1981, Mitich 1991). Downy brome is not currently considered a noxious weed by the state of Utah or any of its counties due to the species omnipresence (Ransom CV, personal communication); however, there is a considerable push by the public and scientific communities alike to develop restoration practices for Utah's invasive annual grass infested rangelands (Davies *et al* 2021, UDAF 2019). This may be partially due to downy bromes abilities to infest disturbed soil and undisturbed soil alike, making it a threat to native grazing lands (Evens *et al.* 2001, Stohlgren *et al.* 2001, Sperry *et al.* 2006).

Downy brome leaves are often flat and densely covered in soft hairs, with ragged, membranous ligules (Whitson *et al.* 2012). The inflorescence is easily recognized by its drooping nature and dense, one-sided panicle. The spikelets themselves are typically between 10 and 20 mm in length with a slight purple color. (Barkworth *et al.* 2007).

Downy brome height at maturation can range from 5 to 60 cm with a fine, fibrous root system (Upadhyaya *et al.* 1986). Predominately self-pollinated, downy brome has been known to produce upwards of 5,000 seeds per plant (Young *et al.* 1987). Even highly stressed plants can still produce a significant number of seeds (Morrow and Stahlman 1984). Furthermore, downy brome can establish an early root system, even though winter months, that can outcompete spring germinating native plants (Harris 1967, Miller *et al.* 2001, Rafferty and Young 2002); however, downy brome does not reproduce through vegetative propagation (Allen and Meyer 2002, Bartlett *et al.* 2002).

While downy brome has been reported in every state, it is typically found in areas that receive, on average, 15 to 56 cm of annual precipitation (Morrow and Stahlman 1984; Upadhyaya *et al.* 1986). This weed also has shown preference to disturbed soils with low salinity and pH (Klemmedson and Smith 1964).

Medusahead (*Taeniatherum caput-medusae),* is another winter annual grass best recognized by its light green color and exaggerated awns, which can range from 3 to 11 cm in length (Barkworth *et al.* 2007). The awns protrude from spike inflorescences, which are 2 to 4 cm long, allowing the seeds to catch onto clothing and fur for dispersal (Cristofaro *et al.* 2020, Komarov 1963). Linear and puberulent leaves connect to the stem of the grass with thin, membranous ligules and inconspicuous auricles (Komarov 1963; Cronquist *et al.* 1977; Hickman 1933).

The first American samples of medusahead were first collected and classified in 1887 Thomas Jefferson Howell. By 1944, reports of medusahead well into the western United States became common-place, and the grass was recognized for the issues it would present for land management (Novak and Sforza 2007, Young 1992).

A key feature of medusahead is its high silica content, which can range from 9% to nearly 19% (Bovey *et al.* 1961, Spackman *et al.* 2020). The results of such high levels include a higher resistance to toxins and UV-B radiation, as well as increased rigidity, defense regulation, and the development of anti-herbivory textures and tastes (Spackman *et al.* 2020). Despite its aggressive nature, Medusahead tends to mature late, usually 2 to 4 weeks after other competitive annual grasses (Young 1992).

Native to the Mediterranean region of Eurasia (Barkworth *et al.* 2007), medusahead typically grows in soils that receive between 25 and 100 cm of annual precipitation (Nafus and Davis 2014, Young 1992). One key ecological feature of medusahead is the plants' slow decomposition rate (Davis and Johnson 2008). This slow rate allows thick layers of thatch to build up, suppressing native vegetation and fueling increasingly frequent wildland fires and reducing overall soil-active herbicide performance (Clark *et al.* 2019a, Davis and Johnson 2008, Young 1992).

It may be important to note that some research has suggested that medusahead had forage value during the early stages of its growth (Brownsey *et al.* 2017, Stonecipher *et al.* 2021). Both studies that arrived at that conclusion propose that chemical retardation of the medusahead lifecycle could allow for increased control via grazing.

As of 2016, medusahead is recognized as a Class 2 noxious weed in the state of Utah. This means that medusahead has "a reasonable distribution in Utah, but [does] not occur everywhere… [therefore it] should be given a high priority for control" (Lowry *et al.* 2016).

Ventenata *(Ventenata dubia* [Leers] Cross), often called North African wiregrass (Harvey 2019), is a winter annual grass that is often confused with downy brome and members of the genera *Avena* and *Trisetum* (Chambers 1985). The species made its first recorded appearance in the Intermountain region around the 1950's; however, it has become much more of a nuisance plant in the past 20 years (Wallace *et al.* 2015).

The leaves of ventenata are typically either flat or involute that connect to the stem with a hyaline ligule that can be as long as 8 mm (Barkworth *et al.* 2007, Hitchcock and Cronquist 1973). One of the species' key features are the glumes, which have seven nerves and obconical pedicels (Chambers 1985).

Ventenata is known for having a very shallow root system, with relatively high silica content (Buell 2021, Mangold *et al.* 2019, Wallace *et al.* 2015). Despite its weedy nature, ventenata seeds have poor long-term viability, with less than 1% of the seeds still able to germinate after 3 years (Wallace *et al.* 2015). Ventenata populations tend to start in area of moderately high soil moisture; however, established populations will expand into drier soils (Fryer 2017, Jones *et al.* 2018).

Despite having infested much of the western and northern United States (Barkworth *et al.* 2007, Jones *et al.* 2018, Koby *et al.* 2019), ventenata is considered endangered or extirpated in many parts of its native European range (Alomran *et al.* 2019, Fryer 2017). Ventenata can often be found on south facing slopes and in rocky clay soils with low nutrient levels, as well as in highly disturbed landscapes (Fryer 2017, Jones *et al.* 2018, Pavek *et al.* 2011).

Further readings on the ecology, biology, and morphology of these weeds can be found in a thesis titled "Control of three invasive annual grasses in Utah using herbicides including indaziflam" (Buell 2021).

Herbicides of Interest

Despite many attempts to find sustainable, non-chemical solutions to the invasive annual grass problem, there had been little success. Studies continue to find that biological controls, such as grazing (Williamson *et al.* 2019), cultural practices, such as controlled burns (Monty *et al.* 2013, Williamson *et al.* 2019), and mechanical methods, such as mowing (Davis *et al.* 2012), are not reliable for managing invasive annuals grasses. As such, there are several different herbicides that are commonly used in the management of rangelands degraded by invasive annual grasses. Several of the main chemicals are described below.

Glyphosate (Accord XRT II, Corteva Agriscience LLC, 9330 Zionsville Rd, Indianapolis, IN, 96268, USA)) is a non-selective herbicide that targets and interrupts the shikimate pathway in plants (Amrhein *et al.* 1980, Espeland and Killian 2015). The shikimate pathway is a critical process in plants, fungi, and bacteria that produces the aromatic amino acids of tryptophan (W), phenylalanine (F), and tyrosine (Y), all of which are important for producing plant hormones (Herrmann *et al.* 1999, Tzin *et al.* 2010). These compounds are not produced naturally in animal cells (Herrmann *et al.* 1999).

Studies have found that glyphosate has a soil absorption coefficient of up to 44,000 L/kg, meaning that when the chemical compound reaches the soil, it becomes tightly bound to the soil particles, and as a result, becomes inert (Battaglin *et al.* 2005, de Jonge *et al* 2001, Mamy and Barriuso 2005). Due to this chemical nature, and the chemicals average half-life of only 47 days, treatments of glyphosate do not provide residual control, thus requiring yearly applications (Sebastian *et al.* 2016, Sebastian *et al.* 2017a, Tu *et al.* 2001). Populations of various weed species have developed resistance to glyphosate, which has led to heavily decreased efficiency in controlling rangeland weeds (Espeland and Killian 2015, Sebastian *et al.* 2017a).

Imazapic (Plateau, BASF Agricultural Products Group, 14385 Wes Port Arthur Rd, Beaumont, TX, 77705, USA) is a selective herbicide that disrupts acetolactate synthase enzymes in treated plants (Mangold *et al.* 2013, Sebastian *et al.* 2016, Tu *et al.* 2001). The acetolactate synthase enzyme is a protein found in plants and micro-organisms that catalyzes the synthesis of the aliphatic amino acids valine (V), leucine (L), and isoleucine (I), and is ultimately critical to plant DNA synthesis (Chipman *et al.* 1998, Zhou *et al.* 2007). Studies have found that imazapic is more effective applied preemergence for invasive grasses (Kyser *et al.* 2007; Mangold *et al.* 2013, Sebastian *et al.* 2016), except for ventenata, where postemergence applications were more effective (Wallace 2016). Much like glyphosate, long-term usage of the herbicide may lead to undesirable resistance in plant populations (Sebastian *et al.* 2017a). Imazapic has a half-life of 120 days, though the half-life can fall to as short as 33 days due to microbial degradation in the soil (American Cyanamid 2015, Tu *et al.* 2001).

Rimsulfuron (Matrix, Corteva Agriscience LLC, 9330 Zionsville Rd, Indianapolis, IN, 96268, USA) is a substituted urea herbicides that interrupts the acetoacetate synthase enzymes, similar to imazapic (Sebastian *et al*. 2016). Rimsulfuron has a half-life of up to 60 days, thus requiring additional treatments for prolonged effects (Sarmah and Sabadie 2002).

Aminopyralid (Milestone, Corteva Agriscience LLC, 9330 Zionsville Rd, Indianapolis, IN 96268 USA) is a systematic auxin-like herbicide that binds to plant growth hormone receptors (Masters *et al.* 2005). Aminopyralid has low acute toxicity (WSDOT 2017) and a particularly short half-life of 30 to 100 days (EPA 2005). While typically applied to control broadleaf weed species, research has shown aminopyralid effects on annual grass seed viability and germination in the soil (Rinella *et al.* 2021)

Indaziflam (Esplanade, Bayer Crop Science, 800 N Lindbergh Blvd, Creve Coeur, MO, 63141, USA) is recently developed cellulose-biosynthesis-inhibiting herbicide (Brabham *et al.* 2014). Indaziflam works by inhibiting cellulose production, which is necessary for generating cell walls, particularly in germinating seeds (Brabham *et al.* 2014). Indaziflam has be shown to be highly effective against invasive winter annual grasses, with many studies supporting the conclusion that indaziflam has little to no long-term negative effects on native vegetation (Clark *et al.* 2019b, Koby *et al.* 2019, Sebastian *et al.* 2017a).

One of the key physical traits of indaziflam is its soil immobility (Alonso *et al.* 2011, González-Delgado *et al.* 2015). A study in particularly sandy soils found that the herbicide rarely moved past the depth of 7 centimeters in the soil (Gonzalez-Delgado *et al.* 2015). This is partially due to the herbicide having low water solubility of 0.0028 g/L at 20ºC (Kaapro and Hall 2012, US EPA 2010), meaning that 357 L of water are needed to dissolve 1 gram of the herbicide. Furthermore, the half-life of indaziflam is likely between 63 and 150 days, though an actual value is not currently agreed upon across literature. (Eckelmann *et al.* 2020, González-Delgado *et al.* 2015, González-Delgado *et al.* 2017, González-Delgado and Shukla 2020, US EPA 2010). Registered as an herbicide in 2010 (US EPA 2010), many researchers have found that indaziflam treatments show consistent invasive annual grass control several years after application (Clark *et al.* 2019, Clark *et al.* 2020, Sebastian *et al.* 2017b). There is also evidence that the indaziflam has increased effectiveness when applied following applications of non-selective herbicides with no residual activity (Seedorf *et al.* 2022). All of this has led some wild- and rangeland managers to have increasing concerns that soil persistence of indaziflam may lead to some undesirable long-term consequences that haven't been observed in the shorter time-framed studies, such as reduced biodiversity and seed bank sterilization (Meyer-Morey *et al.* 2021, Terry *et al.* 2021).

Conditions of Interest

Current rangeland weed management/revegetation efforts in the west are plagued by ever-changing precipitation levels. Starting in June of 2021, the Utah Division of Water Resources declared that 63.97% of the state was in exceptional drought condition, 90.15% of the state was in extremely dry drought condition, and 97.90% of the state was in a severely dry drought condition (Hartman 2023). These numbers were adjusted in 2022, where 5.71% of the state was in exceptional drought conditions, 82.83% of the state was in extremely dry drought conditions, and 99.88% of the state was in a severely dry drought condition (Hartman 2023).

Further data pulled from a National Oceanic and Atmospheric Administration (NOAA) reporting weather station on USU's campus revealed that since the year 2000, 9% of the years have had above normal accumulate precipitation, 27% have had below normal accumulate precipitation, and 64% have had well below normal precipitation (NOAA 2022). While the first half of 2023 saw unexpectedly higher precipitation rates across much of the northern half of the state (Hartman 2023), there is still concerns that the recent droughts might become Utah's new normal.

Precipitation levels can have a major impact on invasive annual grass management. A lack of surface water can have deleterious effects on the shallow root systems of invasive annual grasses (Mohler *et al.* 2021). Most invasive annual grasses have a seedbank longevity of 2-5 years, as such, long-term droughts can clean out a seedbank should they be harsh enough. Likewise, precipitation can have a significant effect on herbicide fate, pushing the herbicide into off-target areas, or into the underground water systems. (Arena *et al.* 2018, Kanissery *et al.* 2020).

The research presented in this thesis was conducted over several years, each with varying climate patterns. All of the data was analyzed using a two-factor repeated measures analysis of variance (ANOVA), looking at plant cover, diversity, etc., as a factor of herbicide treatment and year. Annual cumulative precipitation would have been a major contributor to the different effects that year would have had on the measure data, and considering it leads to a better understanding of the research data.

Research Objectives

To preserve the sustainability of US rangeland weed management, understanding the long-term effects of critical herbicides, such as indaziflam, is necessary if this chemical is going to be widely introduced to weed management programs across the west. Furthermore, adding to the collective knowledge of indaziflam application techniques is also a priority of this study.

The research presented herein was collected from several sites across the Wasatch Mountain Region of northern Utah. The aim of the thesis was 2-fold:

1. Further understand the potential long-term effects, positive and negative, of indaziflam applications, in invasive annual grass invaded landscapes with both high-densities and low-densities of native plant cover, and
2. Explore novel seeding and herbicide application techniques, in pursuit of the best revegetation strategies for indaziflam-based management solutions.

Several sites were used during this research, some of which are continuations of research plots used in Buell 2021, namely a site near Richmond, Utah, that was moderately infested with downy brome, but still supporting a moderate healthy stand of native perennials and desirable grasses; a mildly degraded site near Mt. Sterling, Utah, with recent occurrences of ventenata; and a degraded pastureland in Riverside, Utah, that was predominantly covered in medusahead, with sparse populations of alfalfa and sagebrush. Additional studies were conducted within USU's Research Greenhouse, Weed Science Laboratory, and Center of BioSystems under controlled environments.

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CHAPTER II

Effects Of Indaziflam-Inclusive Herbicide Mixtures On High Plant Diversity Landscapes Multiple Years After Application

Abstract

In recent years, indaziflam has been widely studied as a potential solution for the ever-growing threat of invasive annual grasses in the Western US. While these studies have demonstrated the effectiveness of the herbicide, relatively few of them have followed the herbicide until the end of its 3-5 years of soil persistence. This has led to a knowledge gap, leading to concerns for possible unconsidered, long-term side effects. To determine the long-term environment effects, a random complete block design experiment with 10 different herbicide treatments, including indaziflam, was applied to a healthy, diverse landscape with a mild downy brome infestation. Transect lines were used to annually measure percent coverage of the different species found in each plot. This data was used to determine the impact of different herbicide treatments on the cover of key species and landscape functional groups, diversity, evenness, richness, etc.

These studies found that plots treated with indaziflam, or indaziflam-inclusive mixtures, were able to effectively eliminate downy brome (*Bromus tectorum*), without reducing cover associated with Hooker's balsamroot (*Balsamorhiza hookeri*), Gray's lomatium (*Lomatium grayi*), nor desirable perennial grasses (mostly *Pascopyrum smithii* and *Agropyron cristatum*). Furthermore, while this study did find a correlation between indaziflam applications and decreases in total plant richness and diversity, those changes are explained by the significant decreases in downy brome cover, invasive richness and

minimal to no significant negative effects on desirable richness in those same treatments. The study concluded that, when applied to healthy, diverse landscapes with mild infestations of invasive annual grasses, indaziflam provided effective control of the annual grasses, while maintaining desirable species cover and richness.

Introduction

Downy brome *(Bromus tectorum),* also commonly known as cheatgrass, has been one of the central focuses of weed management in the West, to the point where nearly every agricultural school in the western US is conducting at least some research on the matter. Downy brome is a highly aggressive winter annual grass that is a common invader in millions of acres of western rangelands (Beck n.d.). A Weed Science Society of America's factsheet on the weed attribute its success to the plant's "ability to utilize moisture from the soil's upper layers. Its root system allows most or all the available moisture to be removed from the upper soil profile." (WSSA n.d.). This factsheet also cites the Harris 1967 study, in which downy brome roots were recorded growing at near freezing temperatures. All these traits allow downy brome to quickly outgrow and out compete native species.

Throughout the 1930's, the weed was allowed to make its way through the western US since it provided some grazing in poorer soils where native species might not have thrived as robustly (USFS 1937); however, downy brome is only palatable for a very short period of time and is not eaten by native elk and deer populations (Beck n.d., WSSA n.d.).

As such, many renewed efforts have been made since the late 1900's to bring the downy brome populations back in to check (Kelley *et al.* 2013, Meiter *et al.* 2019). Of the many strategies explored to manage the downy brome, herbicides have come to be seen one of the more promising and cost-effective approaches, especially when used to support the restoration of perennial grasses. (Clements *et al.* 2017, Monaco *et al.* 2017).

Indaziflam was first brought to the herbicide market in 2010 by Bayer CropScience (US EPA 2010). Dr. Rüdiger Scheitza, a member of Bayer's Board of Management was quoted, saying that the herbicide was originally intended to become a "new base herbicide in crops such as fruits and vines, nuts, citrus, olives, and sugar cane" (Bayer CropScience 2010, Parrish *et al.* 2009). Though originally intended for use in agricultural settings, use of indaziflam in rangeland weed management had become a topic of interest among researchers as a replacement for glyphosate and imazapic, two commonly used herbicides commonly in invasive annual grass management (Sebastion *et al* 2016a, Sebastion *et al* 2016b).

By 2021, research focusing on application of indaziflam on western rangelands had become incredibly popular. This is evident in the 2021 Western Society of Weed Science Proceedings, in which "indaziflam" was mentioned on 83% of the posters and in 75% of oral presentations which were listed under the topic of "weeds of range, forest, and natural areas" (WSWS 2021). In those same proceedings, "indaziflam" was the 18th most used word (90 occurrences), only coming in after general terminology such as weed (439 occurrences), control (370 occurrences), herbicide (360 occurrences), crop (336 occurrences), resistance (215 occurrences), and management (182 occurrences) (WSWS 2021).

Indaziflam works by targeting the meristematic regions of germinating seeds and interrupting the cellulose biosynthesis pathways (Brabham *et al.* 2014). This is particularly potent against annual grasses and forbs, while leaving already established perennials with minimal damage (Clark *et al* 2019, Koby *et al* 2019, Sebastian 2017b).

The studies presented in this chapter is a continuation of research published in a previous MS Thesis (Buell 2021), adding an additional three years of observations to her original studies, the purpose of which was understand the ecological impacts of indaziflam and indaziflam-inclusive mixtures on landscape filled with native and naturalized perennial vegetation (Buell 2021). The hypothesis for her studies, and maintained by this continuation, is that indaziflam and indaziflam-inclusive treatments will lead to reduced populations of downy brome without causing deleterious effects to the local ecosystem.

Methods and Materials

Field Study. The study site was located near Richmond, Utah (41º55'59.18" N, 111º46'03.83" W; 1653 m elevation). This site is moderately infested with downy brome; however, it still contains healthy populations of balsamroots (*Balsamorhiza hookeri),* lomatiums (*Lomatium grayi),* and native and naturalized wheatgrasses. The land is a state protected mountainside with minimal human disturbance. Research plots were established in 2017, and repeated in 2018 adjacent to the first, to explore the effects of indaziflam applied alone and in combinations with other herbicides on native forbs and grasses. The same 10 treatments were applied in both iterations of the study (Table 2.1), both applications occurring in late November when desirable perennials had gone dormant, but before the ground froze. All plots here measured 6 m by 30 m. All treatments were applied using a CO_2-pressurized backpack sprayer, calibrated to deliver 234 L/ha at 276 KPa and all treatment included a non-ionic surfactant at 0.25% v/v.

Data Collection. Cover data was collected once a year using line-point intercepts through the center of each plot, with species occurrence recorded every 15 cm. Data was converted to a percentage and then transformed using an arcsin(sqrt) transformation (Equation 2.1) to meet the assumptions of normality:

$$T_i = \sin^{-1}(\sqrt{(d_i)}) \quad \textbf{[2.1]}$$

T_i = transformed data at the i^{th} data point, d_i = i^{th} data point where $0 < d_i < 1$

The plant cover data was then used to calculate key species cover, functional group cover (invasives vs. desirables), richness, diversity, and evenness as metrics of ecosystem health. Specific species of interest that were present at a high enough frequency for independent analysis were downy brome, Hooker's balsamroot, Gray's lomatium, western salsify, sunflower, and prickly lettuce, as well as a lumped category of the desirable perennial grasses, predominately western wheatgrass. Comprehensive lists of all desirable and invasive species identified throughout both repetitions of the study are recorded in tables 2.2 and 2.3, respectively.

Diversity and evenness were calculated using the Shannon Diversity Index (Equation 2.2) and Pielou Evenness Index (Equation 2.3), respectively, as expressed in Wu and Ding 2020:

$$H' = -\sum_i (p_i * \ln(p_i)) \quad \textbf{[2.2]}$$

H' = Diversity Index, p_i = proportion of s made up of the i^{th} species

$$E = H' / \ln(s) \quad \textbf{[2.3]}$$

E = Evenness Index, H' = Diversity Index, s = Number of species

Significance and mean separation were determined using a repeated measures analysis of variance (ANOVA)($\alpha = 0.05$) and a Fisher's LSD, respectively. All data organization and analyses were done using SAS 9.4 (2016). Daily precipitation data from 1993 to 2023 was also collected from a weather station set up in Richmond, UT (41º54’25.2” N, 111º48’36” W; 1405 m elevation) (NOAA 2023).

Study Results

In some instances, analysis showed significant year by treatment interactions, but in other instances only the main effects of herbicide or year or both were significant. Tables 2.4 and 2.5 show all p-values from the ANOVA analyses for all the subsequent tables in runs 1 and 2, respectively.

Individual Species Cover

Downy Brome. In the 2017 study, downy brome was one of a few species of interest that showed in interaction between the different treatments and the years (Table 2.6). All treatments showed an immediate decrease in downy brome cover from the untreated control in the year following application. For the rest of the study, 2019 to 2022, the rimsulfuron, imazapic, and glyphosate alone treatments increased steadily to levels much higher than the control. The indaziflam-inclusive treatments remained significantly lower than the untreated control, two of which remained at 0% downy brome cover for the entirety of the study.

In the 2018 study, the effects regarding downy brome were extremely similar to the 2017 study, showing a significant interaction between treatment and time (Table 2.7). All treatments that included indaziflam initially saw varied responses; however, all of these treatments reduced downy brome cover to 0% by the fourth year of the study. All other treatments saw an initial reduction, but all effects were lost by the third year, with downy brome cover increasing up close to or above the untreated control.

Hooker's Balsamroot. In the 2017 study, Hooker's balsamroot cover data showed significant impacts from the effects of the herbicide treatments and years, not without any interaction between the variables. (Table 2.8). Balsamroot average cover only saw significant deviation from the untreated average cover in the indaziflam + glyphosate and indaziflam + propoxycarbazone treatments, both of with supported a larger percent cover of the perennial forb. All the other treatments were not statistically different from the control. Across time, balsamroot annual averages started at 34% in 2018, rose significantly to 42 and 43% in 2020 and 2021, then fell back to 35% in 2022.

In the 2018 study, balsamroot cover was influenced by the effects of the interaction between herbicide treatment and time (Table 2.9). In 2019, indaziflam-alone was the only treatment to be significantly different for the untreated control, with a higher balsamroot cover. No treatments from their respective untreated controls in 2020 and 2021. Balsamroot cover in all indaziflam-inclusive treatments in 2022 were significantly different from, and higher than, that year's untreated control.

Gray's Lomatium. Gray's lomatium cover in the 2017 trial was affected by treatment and time, but no interaction was found (Table 2.10). Average lomatium cover increased in all indaziflam-inclusive treatments, as well as in the glyphosate treatment. All other treatments were not statistically different from the untreated control, save the imazapic treatment, which was significantly lower than the untreated control. The highest average annual lomatium cover was in 2018, at 5%. Average annual cover for the species then proceeded to decline every year towards 2% in 2022.

In the 2018 trial, lomatium cover was only influenced by time (Table 2.11). Annual average lomatium population was highest in 2019 at 5%. Average annual cover for lomatium in the 2018 study remained significantly lower than the 2018-2019 growing season for the remainder of the study.

Desirable Grasses. Desirable grass cover in the 2017 study was influenced by treatment and time, independently (Table 2.12). Average desirable grass cover was not reduced by indaziflam-alone, propoxycarbazone, rimsulfuron, or imazapic treatments. Reductions were seen in all other treatments; however, the reductions caused by imazapic and indaziflam + rimsulfuron were not different from the indaziflam-alone, propoxycarbazone, and rimsulfuron levels. Higher rates of reduction to the species' cover were recorded in plots treated with glyphosate, indaziflam + imazapic, and indaziflam + glyphosate treatments. Average annual desirable grass cover started high in 2018 at 8%, then dropped by almost half by 2020, 5%, but rebounded back up to their original percent cover in the 2021 and 2021-2022 growing seasons, 8% and 7% respectively.

Desirable grass cover in the 2018 was not influenced by the effects of herbicide treatment or time (Table 2.13).

Sunflower. Sunflower cover data in the 2017 trial was affected independently by treatment and time (2.14). Regarding treatment averages, no treatments differed from the untreated control. Indaziflam-inclusive treatments, likewise, did not different greatly from the other, more conventional herbicides. Average annual sunflower cover was highest in 2018 and 2019 at 3%, dipped in 2020 to near 0%, recovered in 2021 back to 3%, and dropped again in 2022 to 1%.

In the 2018 study, sunflower cover was only impacted by the effects of time (Table 2.15). Annual average sunflower cover across treatments started at 6 and 7% in 2019 and 2020 but fell significantly to 3% in 2021 and 1% in 2022.

Western Salsify. In the 2017 study, Western salsify cover data was influenced by the interaction between the herbicide treatments and time (data not shown); however, the species presence was inconsistent across both time and treatments.

In the 2018 study, salsify cover was only impacted by the effects of time (data not shown); however, the species presence was inconsistent.

Prickly Lettuce. In the 2017 study, prickly lettuce was the impacted by the interaction between the effects of treatments and time (data not shown). Indaziflam-inclusive treatments had reduced prickly lettuce cover of the species to 0% by 2019, and no prickly lettuce plants were recorded in 2021 or 2022 in any of the plots.

In the 2018 study, prickly lettuce cover was independently affected by the effects of herbicide treatments and time (data not shown). Treatments that included indaziflam decreased prickly lettuce cover during 2019 and 2020 and no prickly lettuce plants were recorded in 2021 and 2022 in any of the plots.

Functional Group Cover

Invasive Plant Cover. Over the five years of monitoring the 2017 study, invasive plant cover was independently influenced by the effects of herbicide treatment and time (Table 2.16). For herbicide treatments, all areas treated with indaziflam-inclusive mixture averaged less invasive plant cover than the untreated control. The treatments of propoxycarbazone and glyphosate contained higher invasive plant cover than the control on average. The rimsulfuron and imazapic treatments did not differed from the untreated control in this regard. Annual average invasive plant cover remained between 19 and 24% from 2018 and 2021, then it significantly increased to 41% in 2022.

In the 2018 study, the combined invasive plant cover was significantly affected by the interaction between herbicide treatment and time (Table 2.17). During the first year, all treatments significantly reduced invasive plant cover compared to the untreated control, expect in the glyphosate, indaziflam + rimsulfuron and indaziflam + imazapic treatments. No treatments differed from their respective untreated controls in 2020 and 2021. By the 2022, reductions in invasive plant cover were recorded in all indaziflam-inclusive treatments. All other herbicides did not correlate with reduction in invasive plant cover in this year.

Desirable Plant Cover. Desirable plant cover data in the 2017 trial was independently influenced by the effects of herbicide treatment and time (Table 2.18). The indaziflam + glyphosate treatment was the only treatment to maintain a desirable species average cover significantly higher that of the untreated control. All other indaziflam-inclusive treatments were not significantly different from the control. Glyphosate-alone was the only treatment to have significantly deleterious effect on the desirable species functional group. Annual desirable plant cover remained between 65 and 68% (no significant difference) between 2018 and 2021, then significantly dropped to 55% in 2022.

For the 2018 study, desirable plant cover was significantly impacted by the effects of the interaction between the herbicide treatment and time (Table 2.19). In 2019, only the indaziflam-alone treatment was significantly different from, and higher than, the untreated control. No treatments different for the control in 2020. In 2021, both indaziflam-alone and indaziflam + rimsulfuron led to increases in desirable plant cover when compared to that year’s untreated control. In 2022, all indaziflam-inclusive treatments correlated with significant increases in desirable plant cover from the untreated control.

Plant Community Metrics

Richness. In the 2017 study, total plant richness data was influenced by the interaction between the herbicide treatments and time (Table 2.20). No treatments differed from the untreated control in 2018. In 2019, all indaziflam-inclusive treatments resulted in significant reductions from the untreated control. In 2020, the only treatment to differ from the untreated control was the propoxycarbazone treatment, which yielded significantly higher richness than the untreated control. In 2021 and 2022, only the indaziflam + glyphosate treatment correlated with reductions in total plant richness.

In the 2017 study, the invasive plant richness data was independently influenced treatment and time, with no showed interaction (Table 2.21). Of all the treatments, only the treatments that included indaziflam maintained significantly reduced invasive species richness. All other treatments were equal to or significantly higher than the untreated control, with glyphosate and rimsulfuron having the highest average invasive species richness scores. Average invasive richness by year did not fluctuate much despite being significant, with a low of 4 in 2018 and 2020-2022, and high of 5 in 2019.

Desirable plant richness levels in the 2017 study independently affected by treatment and time (Table 2.22). Average desirable species richness was significantly reduced in plots treated with the glyphosate-alone, indaziflam + propoxycarbazone, and indaziflam + glyphosate treatments. All other treatments were not significantly different from the untreated control. Average annual desirable richness had a high of 6 in 2018-2019 and 2021-2022, and a low of 5 in 2020.

In the 2018 trial, total plant richness was influenced by the effects of the interaction between herbicide treatment and time (Table 2.23). In 2019, reductions in total plant richness from the untreated control was found in propoxycarbazone, imazapic, and indaziflam + glyphosate treatments. In 2020, only the indaziflam + glyphosate treatment correlated with reductions from the untreated control. In 2021, the indaziflam + imazapic was the only treatment with reductions from the control. In 2022, no treatments differed from the untreated control.

In the 2018 trial, the invasive plant richness data was impacted by the interaction between herbicide treatments and time (Table 2.24). The only treatments to lead to reductions in invasive plant richness from the untreated control were the indaziflam + glyphosate treatment in 2020, indaziflam-alone and indaziflam + imazapic in 2021, and indaziflam-alone, again, in 2022. All other treatments did not differ from the untreated controls of their respective years.

In the 2018 study, desirable plant richness was not influenced by the effects of either herbicide treatment or time (Table 2.25).

Total Plant Diversity. In the 2017 trial, total plant diversity was independently influenced by the effects of herbicide treatment and time (Table 2.26). Regarding treatment averages, all treatments, except propoxycarbazone and rimsulfuron, resulted in a reduction of diversity from the untreated control. Annual average diversity scores began at 1.59 and 1.64 in 2018 and 2019, respectively, but fell significantly to 1.45 and 1.41 in 2020 and 2021. The diversity index did rise significant in 2022, but only to 1.54.

Total plant diversity in the 2018 study was only affected by time (Table 2.27). Average annual total plant diversity had a high between 1.82 and 1.86 between 2019 and 2021, and a significant low of 1.64 in 2022.

Plant Species Evenness. In the 2017 study, plant species evenness was independently influenced by herbicide treatment and time (Table 2.28). All treatments that included indaziflam mixed with another herbicide, as well as the glyphosate treatment, had recorded reductions in total plant species evenness. All other treatments, including the indaziflam alone treatment, did not differ from the untreated control. Average annual plant species evenness started high between 0.67-0.70 (not significantly different) from 2018 to 2020 before significantly dropping in 2021 to 0.63, before rising significantly in 2022 to 0.67.

The 2018 total plant evenness data was only affected by time (Table 2.29). Annual average plant evenness was highest in 2019 at 0.86, dropped in 2020 and 2021 at 0.82 and 0.84 respectively, then fell significantly in 2022 to 0.76.

Discussion

Precipitation. When time was prevalent as a factor of plant cover, it is likely that precipitation was the major driving force behind that. Figure 2.1 shows the annual precipitation for each growing year (July – June) for every year of the study, as well as a 30-year accumulative average. In many of the species, a drop in cover is often noted in the data collected at the end of the 2020-2021 growing season, when precipitation was at its lowest. This was almost always followed by a recovery in 2022, as precipitation increased to near that of the 30-year average.

Treatment effects on downy brome. The explicit goal of weed management in native wildlands is to prevent the loss of natural recourses such as habitat, forage, and other ecological services (Bishop 2023). Invasive grasses provide a unique threat because of their early germination strategies, poor forgeability, and copious contribution to wildfire fuels. In this research, indaziflam and indaziflam-inclusive herbicide mixtures all provided excellent control of downy brome for every year in both iterations of the study, spanning the expected soil-persistence period of the herbicide. In the 2017 trail, evidence of the breakdown of indaziflam was present during the final year, and a few of the plots began to redevelop small populations of downy brome. Further monitoring or even follow-up applications may provide interesting insight into the long-term control of invasive annual grasses.

Treatment effects on non-target perennial grasses. What is important to notice about the desirable grass cover is that while indaziflam-inclusive mixed did appear to have a negative effect in the 2017 study, these results were not repeated in the 2018. Of the 2017 treatments, those of indaziflam mixed with other conventional herbicides were not significantly different than when those herbicides were applied alone, expect in the case of imazapic. It is also worth noting that indaziflam alone did not lead to a reduction in desirable grass cover. While further testing may be needed to solidly the effects of indaziflam on non-target perennial grasses, this study did not find enough evidence to suggest a significant long-term negative effect.

Treatment effects on perennial forbs. The study found no evidence that indaziflam applications had a negative impact on the two dominate perennial forb populations, Hooker's balsamroot, and Gray’s lomatium. There does appears to be competition between the native species, as general growth in balsamroots was often correlated with decreases in lomatiums and desirable grasses. This was especially the case in indaziflam-treated plots, where competition from annual weeds was significantly reduced. The balsamroots were the largest and most robust plant species in the area, and as a result, were the most competitive when it came to growth and resource acquisition.

While no seedbank study was conducted, balsamroots are an extremely long lived genus of plants, producing seeds for 20-30 years after maturation (Monsen *et al.* 2004). Some studies have also found that balsamroot seeds do not have a long persistence period in the soil (Kitchen and Monsen 1996). Considering that ecology, it is unlikely that indaziflam would have an effected on established balsamroot species.

Treatment effects on annual forbs. Annual forbs did not play a significant role in this study. Two of the three annual species, prickly lettuce and western salsify were not detected in several years of the study. The third main annual in this study, common sunflower, likewise made up a very small percentage of the landscape cover, and its presence varied greatly between herbicide treatments, even in those including indaziflam.

Treatment effects on community richness. While this study did find a correlation between reductions in total plant richness and applications including indaziflam in both iterations, those reduction were related to the removal of the target species, downy brome. The near complete removal of downy brome from the ecosystem provides a clear explanation for the significant reductions in total plant richness and invasive plant richness, as, even in this healthy landscape, there was rarely more the 5-6 dominate species in any given area.

Treatment effects on landscape diversity and evenness. The Shannon's diversity index was significantly lower in plots treated with indaziflam. However, the actual effect of indaziflam on biodiversity is become clearer when the Shannon diversity index, which is a measure of entropy, is converted into the number of equally-frequent species, following the processes explained in Jost 2006 (Equation 2.4).

$$D = \exp(H') \quad \textbf{[3.4]}$$

D = the effective number of species, H' = Diversity index

When the Shannon diversity index is converted into the effective number of species, the data shows that plots treated with indaziflam-alone have only lost a single species, except during the 2021 of the 2018 study, wherein the continued drought led to widespread reduction in species. In the 2017 study, plots treated with indaziflam mixed with other herbicides only resulted in the loss of 0-1 effective species, except indaziflam + glyphosate, which showed a loss of 2 species. The 2018 study showed that indaziflam mixtures resulted in the loss of 2 species, with the indaziflam + glyphosate reporting a loss of 3 effective species. There is a correlation between the loss of effective species and the application of glyphosate, however, the data also shows that glyphosate does not provide long term control of downy brome and is likely affecting off-target species.

Management Implications. In a recent publication from Montana State University, they stated "we conclude that indaziflam should likely be reserved for use in areas that are severely invaded and have seedbanks that are composed of non-desirable species rather than diverse, native mountain sagebrush communities." (Meyer-Morey *et al.* 2021). The data presented in this chapter provide evidence to the contrary. This study has found that indaziflam has a practical benefit when applied to healthy, native landscapes with only mild invasive annual grass infestations. The results demonstrate that proactive indaziflam applications can limit downy brome spread while leaving desirable perennial forbs and grasses largely unaffected.

While diversity is an important metric, and, as put by Meyer-Morey *et al.* 2021, “[plant] communities that are higher in diversity are typically more resistant to ecosystem alteration”, an over focus on diversity may deter land managers from using indaziflam on healthy landscapes with low species richness to control the spread of downy brome. Understanding that, in some cases, reductions in richness and diversity can lead to a healthier ecosystem is essential. Future studies should consider the soil seedbank longevity of native perennials, as well as measuring competition between native species when indaziflam is treated to healthy landscapes.

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Data Tables

Table 2.1. Treatments applied to control downy brome in a largely intact plant community in 2017 and 2018 near Richmond, UT.

Treatments*	Rate
	g ai ha^{-1}
Untreated	N/A
Indaziflam	102
Propoxycarbazone	59
Rimsulfuron	70
Imazapic	175
Glyphosate	532
Indaziflam + Propoxycarbazone	102 + 59
Indaziflam + Rimsulfuron	102 + 70
Indaziflam + Imazapic	102 + 175
Indaziflam + Glyphosate	102 + 532

* All treatments included a non-ionic surfactant at 0.25% v/v and were applied in late November of their respective years.

Table 2.2. Comprehensive list of all desirable species identified in a study to control downy brome started in 2017 and 2018 near Richmond, UT.

Desirable Species*			
Common Name	Scientific Name	Common Name	Scientific Name
Western yarrow	*Achillea millefolium*	Bastard toadflax	*Comandra umbellata*
Crested wheatgrass	*Agropyron cristatum*	Hawksbeard	*Crepis* sp.
Wild onion	*Allium canadense*	Sticky geranium	*Geranium viscosissimum*
Sagewort	*Artemisis annua*	Curlycup gumweed	*Grindelia squarrosa*
Silver sage	*Artemisia cana*	Wild onion	*Allium canadense*
Big sagebrush	*Artemisia tridentata*	Sunflower	*Helianthus annuus*
Hooker’s balsamroot	*Balsamorhiza hookeri*	Gray’s lomatium	*Lomatium grayi*
Arrowleaf	*Balsamorhiza sagittate*	Lupine	*Lupinus* sp.
Smooth brome	*Bromus inermis*	Bluegrasses	*Poa* spp.
Blue camas	*Camassia quamash*	Deathcamas	*Toxicoscordion paniculatum*
Collomia	*Collomia* spp.	Mule’s ear	*Wyethia mollis*

*Unable to fully identify: “low grow”, “false sunflower”, “false dandelion”, “stickseed”, and “mountain trumpet”.

Table 2.3. Comprehensive list of all invasive species identified in a study to control downy brome started in 2017 and 2018 near Richmond, UT.

Invasive Species*			
Common Name	Scientific Name	Common Name	Scientific Name
Alyssum	*Alyssum sp.*	Field gromwell	*Lithospermum arvense*
Rattlesnake brome	*Bromus briziformis*	Forget-me-not	*Myosotis scorpioide*
Downy brome	*Bromus tectorum*	Fireweed	*Onagranceae* spp.
Flixweed	*Descurainia sophia*	Bulbous bluegrass	*Poa bulbosa*
Filaree	*Erodium cicutarium*	Wild Rose	*Rosa acicularis*
Catchweed	*Galium aparine*	Medusahead	*Taeniatherum caput-medusae*
Dyer's woad	*Isatis tinctoria*	Salsify	*Tragopogon dubius*
Prickly lettuce	*Lactuca serriola*	Speedwell	*Veronica* sp.

*Unable to fully identify: “little mustard” “willowweed”, and “unknown borage”.

Table 2.4. P-values for treatment, year, and the treatment by year interaction for the response variables for tables produced from data collected from a study to control downy brome in near Richmond, UT. The study was started in 2017.

	Sources of Variation		
Table	Treatment	Year	Treatment: Year
2.6 - Downy brome	<0.01*	<0.01*	<0.01*
2.8- Hooker’s balsamroot	<0.01*	<0.01*	0.99
2.10 - Gray’s lomatium	<0.01*	<0.01*	0.14
2.12 - Desirable grasses	<0.01*	0.02*	0.71
2.14 - Sunflower	0.02	<0.01*	0.92
Western salsify (not shown)	<0.01*	<0.01*	0.33
Prickly lettuce (not shown)	<0.01*	<0.01*	<0.01*
2.16 – Invasive cover	<0.01*	<0.01*	0.68
2.18 - Desirable cover	<0.01*	<0.01*	1.00
2.20 – Total richness	<0.01*	<0.01*	0.05*
2.21 - Invasive richness	<0.01*	<0.01*	0.07
2.22 - Desirable richness	0.05*	<0.01*	0.91
2.26 - Diversity	<0.01*	<0.01*	0.24
2.28 - Evenness	<0.01*	<0.01*	0.61

*P-value less than 0.05

Table 2.5. P-values for treatment, year, and the treatment by year interaction for the response variables for tables produced from data collected from a study to control downy brome in near Richmond, UT. The study was started in 2018.

	Sources of Variation		
Table	Treatment	Year	Treatment: Year
2.7 - Downy brome	<0.01*	<0.01*	<0.01*
2.9- Hooker’s balsamroot	<0.01*	0.09	<0.01*
2.11 - Gray’s lomatium	0.46	<0.01*	0.19
2.13 - Desirable grasses	0.43	0.32	0.43
2.15 - Sunflower	0.14	<0.01*	0.99
Western salsify (not shown)	0.09	<0.01*	0.98
Prickly lettuce (not shown)	<0.01*	<0.01*	0.10
2.17 – Invasive cover	<0.01*	<0.01*	<0.01*
2.19 - Desirable cover	0.02*	<0.01*	<0.01*
2.23 – Total richness	<0.01*	0.34	0.01*
2.24 - Invasive richness	0.01*	0.07	0.02*
2.25 - Desirable richness	0.18	0.34	0.08
2.27 - Diversity	0.10	<0.01*	0.05
2.29 - Evenness	0.06	<0.01*	0.05

*P-value less than 0.05

Table 2.6. *Bromus tectorum* cover as a response to the interaction between treatments and time from a study to control downy brome near Richmond, UT. The study was started in 2017 and data was collected in May every year following treatment application.

		Bromus tectorum (downy brome) cover†									
Treatments*	Rate	2018		2019		2020		2021		2022	
	g ai ha^{-1}	%									
Untreated	-	20	e-i	18	f-j	9	j	14	hij	23	d-h
Indaziflam	102	4	k	0	l	0	l	1	l	1	l
Propoxycarbazone	59	13	ij	20	e-j	20	e-j	24	c-f	36	abc
Rimsulfuron	70	2	kl	15	f-j	17	f-j	21	e-i	32	bcd
Imazapic	175	4	k	18	f-j	14	g-j	12	Ij	42	ab
Glyphosate	210	1	l	23	d-g	29	cde	30	cde	47	a
Indaz + Propoxy	102 + 59	0	l	0	l	0	l	0	l	2	kl
Indaz + Rimsulf	102 + 70	0	l	0	l	0	l	0	l	2	kl
Indaz + Imaz	102 + 175	0	l	0	l	0	l	0	l	0	l
Indaz + Glypho	102 + 210	0	l	0	l	0	l	0	l	0	l
Yearly average		4		10		9		11		19	

* All treatments included a non-ionic surfactant at 0.25% v/v.

† Values labeled with the same letter are not significantly different according to Fisher's LSD at $\alpha = 0.05$.

Table 2.7. *Bromus tectorum* cover as a response to the interaction between treatment and time from a study to control downy brome near Richmond, UT. The study was started in 2018 and data was collected in May every year following treatment application.

		Bromus tectorum (downy brome) cover†							
Treatments*	Rate	2019		2020		2021		2022	
	g ai ha^{-1}	%							
Untreated	-	14	d-g	9	e-h	26	bc	34	ab
Indaziflam	102	3	ghi	9	fgh	0	i	0	i
Propoxycarbazone	59	11	f-i	5	hi	20	b-e	30	b
Rimsulfuron	70	9	e-h	12	c-f	26	bc	33	ab
Imazapic	175	0	i	0	i	24	bcd	37	ab
Glyphosate	210	8	fgh	3	ghi	34	ab	52	a
Indaz + Propoxy	102 + 59	6	f-i	8	f-i	0	i	0	i
Indaz + Rimsulf	102 + 70	10	f-i	7	f-i	0	i	0	i
Indaz + Imaz	102 + 175	8	fgh	13	c-f	0	i	0	i
Indaz + Glypho	102 + 210	0	i	0	i	0	i	0	i
Yearly average		7		6		13		19	

* All treatments included a non-ionic surfactant at 0.25% v/v.

† Values labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 2.8. *Balsamorhiza hookeri* cover as a response to treatment and time from a study to control downy brome near Richmond, UT. The study was started in 2017 and data was collected in May every year following treatment application.

		Balsamorhiza hookeri (Hooker's balsamroot) cover					
Treatments*	Rate	2018	2019	2020	2021	2022	μ Separation[†]
	g ai ha^{-1}	%					
Untreated	-	31	40	35	38	30	35 cde
Indaziflam	102	35	36	46	44	45	41 bc
Propoxycarbazone	59	31	33	34	34	23	31 e
Rimsulfuron	70	33	31	39	40	25	34 de
Imazapic	175	38	36	41	35	29	36 cde
Glyphosate	210	37	40	40	39	23	36 cde
Indaz + Propoxy	102 + 59	38	44	46	49	41	44 ab
Indaz + Rimsulf	102 + 70	32	39	40	44	40	39 b-e
Indaz + Imaz	102 + 175	33	38	44	46	43	41 bcd
Indaz + Glypho	102 + 210	38	53	56	61	47	51 a
Yearly average[‡]		34 b	39 ab	42 a	43 a	35 b	

* All treatments included a non-ionic surfactant at 0.25% v/v

[†] Values under this header labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

[‡] Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 2.9. *Balsamorhiza hookeri* cover as a response to the interaction of treatment and time from a study to control downy brome near Richmond, UT. The study was started in 2018 and data was collected in May every year following treatment application.

		Balsamorhiza hookeri (Hooker's balsamroot) cover[†]							
Treatments*	Rate	2019		2020		2021		2022	
	g ai ha^{-1}	%							
Untreated	-	23	f-j	28	b-j	28	d-j	24	ijk
Indaziflam	102	27	a-e	27	ab	31	b-j	36	a-g
Propoxycarbazone	59	27	g-k	30	a-f	25	h-k	28	e-j
Rimsulfuron	70	26	c-j	28	b-j	22	jk	18	k
Imazapic	175	33	ijk	34	b-j	32	b-j	25	ijk
Glyphosate	210	34	g-k	36	c-j	33	b-j	23	jk
Indaz + Propoxy	102 + 59	28	a-h	33	a-f	33	b-j	39	a-e
Indaz + Rimsulf	102 + 70	40	f-k	38	ijk	43	ab	46	a
Indaz + Imaz	102 + 175	28	f-j	36	c-j	47	a	34	b-i
Indaz + Glypho	102 + 210	25	b-j	37	b-j	40	abc	39	a-d
Yearly average		29		33		33		31	

* All treatments included a non-ionic surfactant at 0.25% v/v.

[†] Values under this header labeled with the same letter are not significantly different according to Fisher's LSD at $\alpha = 0.05$.

Table 2.10. *Lomatium grayi* cover as a response to treatments and time from a study to control downy brome near Richmond, UT. The study was started in 2017 and data was collected in May every year following treatment application.

		Lomatium grayi (Gray's lomatium) cover					
Treatments*	Rate	2018	2019	2020	2021	2022	μ Separation†
	g ai ha^{-1}	%					
Untreated	-	2	3	3	1	0	2 c
Indaziflam	102	5	5	3	2	3	4 b
Propoxycarbazone	59	4	4	1	2	0	2 c
Rimsulfuron	70	4	2	2	2	0	2 cd
Imazapic	175	3	1	0	1	0	1 d
Glyphosate	210	5	3	3	2	0	3 b
Indaz + Propoxy	102 + 59	6	6	4	4	2	4 b
Indaz + Rimsulf	102 + 70	5	5	3	3	2	3 b
Indaz + Imaz	102 + 175	6	2	3	1	5	3 b
Indaz + Glypho	102 + 210	12	6	4	3	6	6 a
Yearly average‡		5 a	4 b	2 c	2 cd	2 d	

* All treatments included a non-ionic surfactant at 0.25% v/v

† Values under this header labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

‡ Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 2.11. *Lomatium grayi* cover as a response to treatments from a study to control downy brome near Richmond, UT. The study was started in 2018 and data was collected in May every year following treatment application.

		Lomatium grayi (Gray's lomatium) cover			
Treatments*	Rate	2019	2020	2021	2022
	g ai ha^{-1}	%			
Untreated	-	4	1	2	1
Indaziflam	102	6	3	4	2
Propoxycarbazone	59	5	1	3	1
Rimsulfuron	70	3	1	2	1
Imazapic	175	4	0	1	0
Glyphosate	210	6	1	3	0
Indaz + Propoxy	102 + 59	6	2	4	2
Indaz + Rimsulf	102 + 70	3	1	2	1
Indaz + Imaz	102 + 175	3	0	4	1
Indaz + Glypho	102 + 210	10	5	3	3
Yearly average[‡]		5 a	2 c	3 b	1 d

* All treatments included a non-ionic surfactant at 0.25% v/v.

[†] Values under this header labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

[‡] Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 2.12. Desirable grass cover as a response to treatments and time from a study to control downy brome near Richmond, UT. The study was started in 2017 and data was collected in May every year following treatment application.

		Desirable grass cover					
Treatments*	Rate	2018	2019	2020	2021	2022	μ Separation[†]
	g ai ha^{-1}			%			
Untreated	-	16	8	7	14	9	11 a
Indaziflam	102	11	9	5	10	9	9 abc
Propoxycarbazone	59	1	7	10	11	9	10 ab
Rimsulfuron	70	11	7	6	9	6	8 abc
Imazapic	175	11	7	8	9	6	8 abc
Glyphosate	210	2	1	2	6	6	3 d
Indaz + Propoxy	102 + 59	9	3	2	7	9	6 c
Indaz + Rimsulf	102 + 70	10	8	4	7	6	7 bc
Indaz + Imaz	102 + 175	2	4	4	3	2	3 d
Indaz + Glypho	102 + 210	2	2	2	4	8	3 d
Yearly average[‡]		8 a	6 bc	5 c	8 ab	7 ab	

* All treatments included a non-ionic surfactant at 0.25% v/v

[†] Values under this header labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

[‡] Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 2.13. Desirable grass cover as a response to treatments from a study to control downy brome near Richmond, UT. The study was started in 2018 and data was collected in May every year following treatment application.

		Desirable grasses cover			
Treatments*	Rate	2019	2020	2021	2022
	g ai ha^{-1}	%			
Untreated	-	10	14	12	8
Indaziflam	102	14	13	10	13
Propoxycarbazone	59	21	25	22	15
Rimsulfuron	70	19	20	17	16
Imazapic	175	13	13	15	13
Glyphosate	210	5	7	6	6
Indaz + Propoxy	102 + 59	17	17	14	16
Indaz + Rimsulf	102 + 70	13	15	13	11
Indaz + Imaz	102 + 175	8	15	7	12
Indaz + Glypho	102 + 210	3	5	5	7
Yearly average		12	14	12	12

* All treatments included a non-ionic surfactant at 0.25% v/v

[†] Values under this header labeled with the same letter are not significantly different according to Fisher's LSD at $\alpha = 0.05$.

Table 2.14. *Helianthus annuus* cover as a response to treatments and time from a study to control downy brome near Richmond, UT. The study was started in 2017 and data was collected in May every year following treatment application.

		Helianthus annuus (common sunflower) cover						
Treatments*	Rate	2018	2019	2020	2021	2022	μ Separation[†]	
	g ai ha^{-1}	%						
Untreated	-	2	2	0	2	0	1	abc
Indaziflam	102	3	4	0	6	2	3	ab
Propoxycarbazone	59	1	3	0	1	1	1	abc
Rimsulfuron	70	1	1	0	0	0	0	c
Imazapic	175	4	4	0	3	2	3	ab
Glyphosate	210	2	1	0	1	0	1	bc
Indaz + Propoxy	102 + 59	0	0	0	1	1	0	c
Indaz + Rimsulf	102 + 70	6	6	0	7	2	4	a
Indaz + Imaz	102 + 175	6	8	0	7	3	5	a
Indaz + Glypho	102 + 210	2	2	0	2	0	1	bc
Yearly average[‡]		3 a	3 a	0 d	3 b	1 c		

* All treatments included a non-ionic surfactant at 0.25% v/v.

[†] Values under this header labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

[‡] Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 2.15. *Helianthus annuus* cover as a response to time from a study to control downy brome near Richmond, UT. The study was started in 2018 and data was collected in May every year following treatment application.

		Helianthus annuus (common sunflower) cover							
Treatments*	Rate	2019		2020		2021		2022	
	g ai ha^{-1}	%							
Untreated	-	2		3		0		1	
Indaziflam	102	12		15		9		6	
Propoxycarbazone	59	5		7		4		1	
Rimsulfuron	70	9		8		2		2	
Imazapic	175	8		9		4		1	
Glyphosate	210	11		11		5		2	
Indaz + Propoxy	102 + 59	4		2		0		1	
Indaz + Rimsulf	102 + 70	8		13		3		1	
Indaz + Imaz	102 + 175	2		2		0		1	
Indaz + Glypho	102 + 210	0		0		0		0	
Yearly average[‡]		6	b	7	a	3	c	1	c

* All treatments included a non-ionic surfactant at 0.25% v/v.

[†] Values under this header labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

[‡] Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 2.16. Invasive plant cover as a response to treatments and time from a study to control downy brome near Richmond, UT. The study was started in 2017 and data was collected in May every year following treatment application.

		Invasive plant cover					
Treatments*	Rate	2018	2019	2020	2021	2022	μ Separation[†]
	g ai ha^{-1}	%					
Untreated	-	30	27	21	20	44	28 c
Indaziflam	102	19	21	12	12	31	19 d
Propoxycarbazone	59	31	32	30	33	56	36 ab
Rimsulfuron	70	21	38	33	27	55	35 abc
Imazapic	175	21	30	25	31	53	32 bc
Glyphosate	210	24	39	39	36	58	39 a
Indaz + Propoxy	102 + 59	16	14	33	10	32	19 d
Indaz + Rimsulf	102 + 70	5	15	8	10	30	13 ef
Indaz + Imaz	102 + 175	15	13	12	10	28	16 de
Indaz + Glypho	102 + 210	8	8	8	3	24	10 f
Yearly average[‡]		19 c	24 b	21 bc	19 c	41 a	

* All treatments included a non-ionic surfactant at 0.25% v/v.

[†] Values labeled with the same letter are not significantly different according to Fisher's LSD at $\alpha = 0.05$.

[‡] Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at $\alpha = 0.05$.

Table 2.17. Invasive plant cover as a response to the interaction of treatments by time from a study to control downy brome near Richmond, UT. The study was started in 2018 and data was collected in May every year following treatment application.

		Invasive plant cover†							
Treatments*	Rate	2019		2020		2021		2022	
	g ai ha^{-1}	%							
Untreated	-	29	e-i	24	f-j	35	d-g	56	ab
Indaziflam	102	10	k-o	24	f-j	3	o	30	d-i
Propoxycarbazone	59	19	h-m	22	g-l	25	f-j	44	bcd
Rimsulfuron	70	19	h-m	22	g-l	35	d-g	57	ab
Imazapic	175	10	k-o	17	i-n	32	d-h	52	abc
Glyphosate	210	23	g-k	17	i-n	39	cde	64	a
Indaz + Propoxy	102 + 59	19	h-n	19	h-m	5	no	26	e-j
Indaz + Rimsulf	102 + 70	22	g-l	29	e-i	6	mno	25	f-j
Indaz + Imaz	102 + 175	25	f-j	32	d-h	6	mno	38	def
Indaz + Glypho	102 + 210	8	l-o	15	j-o	9	l-o	35	d-g
Yearly average		19		22		19		43	

* All treatments included a non-ionic surfactant at 0.25% v/v.

† Values labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 2.18. Desirable plant cover as a response to treatments and time from a study to control downy brome near Richmond, UT. The study was started in 2017 and data was collected in May every year following treatment application.

		Desirable plant cover					
Treatments*	Rate	2018	2019	2020	2021	2022	μ Separation[†]
	g ai ha^{-1}	%					
Untreated	-	64	68	64	69	55	64 bc
Indaziflam	102	65	65	74	71	65	68 ab
Propoxycarbazone	59	62	65	65	61	43	59 cd
Rimsulfuron	70	60	57	62	64	43	57 cd
Imazapic	175	70	66	65	61	46	62 bcd
Glyphosate	210	60	58	57	58	40	55 d
Indaz + Propoxy	102 + 59	67	69	67	71	64	68 ab
Indaz + Rimsulf	102 + 70	67	69	72	71	61	68 ab
Indaz + Imaz	102 + 175	62	70	72	72	65	68 ab
Indaz + Glypho	102 + 210	69	76	78	81	67	74 a
Yearly average[‡]		65 a	68 a	66 a	68 a	55 b	

* All treatments included a non-ionic surfactant at 0.25% v/v.

[†] Values labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

[‡] Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 2.19. Desirable plant cover as a response to the interactions of treatments by time from a study to control downy brome near Richmond, UT. The study was started in 2018 and data was collected in May every year following treatment application.

		Desirable plant cover[†]			
Treatments*	Rate	2019	2020	2021	2022
	g ai ha^{-1}	%			
Untreated	-	59 c-g	66 a-f	54 f-i	43 hij
Indaziflam	102	75 a	70 a-e	71 a-d	63 a-f
Propoxycarbazone	59	59 c-g	64 a-f	63 a-f	56 e-i
Rimsulfuron	70	65 a-f	68 a-f	57 d-i	42 ij
Imazapic	175	60 b-g	67 a-f	60 b-fg	47 g-j
Glyphosate	210	68 a-f	74 ab	56 e-i	34 j
Indaz + Propoxy	102 + 59	67 a-f	68 a-f	64 a-f	66 a-f
Indaz + Rimsulf	102 + 70	55 e-i	54 f-i	72 abc	69 a-f
Indaz + Imaz	102 + 175	59 c-g	59 c-g	67 a-f	58 d-h
Indaz + Glypho	102 + 210	59 d-g	68 a-f	55 f-i	59 c-g
Yearly average		63	66	62	54

* All treatments included a non-ionic surfactant at 0.25% v/v.

[†] Values labeled with the same letter are not significantly different according to Fisher’s LSD at α = 0.05.

Table 2.20. Total plant richness as a response to the interaction of treatments by time from a study to control downy brome near Richmond, UT. The study was started in 2017 and data was collected in May every year following treatment application.

		Total plant richness[†]									
Treatments*	Rate	2018		2019		2020		2021		2022	
	g ai ha^{-1}	number of species									
Untreated	-	10	d-j	14	ab	9	g-l	11	c-h	11	c-g
Indaziflam	102	9	f-l	10	e-l	8	i-l	10	d-j	11	d-i
Propoxycarbazone	59	12	a-d	13	abc	12	b-e	10	e-k	11	d-h
Rimsulfuron	70	11	c-h	14	ab	10	g-l	10	e-k	11	c-g
Imazapic	175	12	b-f	12	a-d	10	e-l	11	c-g	9	g-l
Glyphosate	210	12	b-f	15	a	10	e-k	10	d-j	10	e-l
Indaz + Propoxy	102 + 59	8	jkl	9	g-l	8	kl	9	g-l	10	e-k
Indaz + Rimsulf	102 + 70	8	jkl	9	g-l	8	jkl	9	f-l	10	d-j
Indaz + Imaz	102 + 175	9	h-l	10	d-j	9	f-l	9	g-l	11	c-g
Indaz + Glypho	102 + 210	8	jkl	9	g-l	7	l	8	kl	7	l
Yearly average		10		11		9		10		10	

* All treatments included a non-ionic surfactant at 0.25% v/v.

[†] Values labeled with the same letter are not significantly different according to Fisher’s LSD at α = 0.05.

Table 2.21. Invasive plant richness as a response to treatments and time from a study to control downy brome near Richmond, UT. The study was started in 2017 and data was collected in May every year following treatment application.

		Invasive richness					
Treatments*	Rate	2018	2019	2020	2021	2022	μ Separation[†]
	g ai ha^{-1}	number of species					
Untreated	-	4	6	4	4	5	5 c
Indaziflam	102	4	4	3	4	4	4 d
Propoxycarbazone	59	5	7	3	4	5	5 bc
Rimsulfuron	70	5	7	6	5	5	6 ab
Imazapic	175	5	5	4	5	4	4 cd
Glyphosate	210	5	8	6	5	5	6 a
Indaz + Propoxy	102 + 59	2	4	3	3	4	3 f
Indaz + Rimsulf	102 + 70	2	3	3	3	4	3 ef
Indaz + Imaz	102 + 175	2	3	3	3	4	3 ef
Indaz + Glypho	102 + 210	2	3	2	3	3	3 e
Yearly average[‡]		4 b	5 a	4 b	4 b	4 a	

* All treatments included a non-ionic surfactant at 0.25% v/v.

[†] Values labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

[‡] Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 2.22. Desirable plant richness as a response to treatments and time from a study to control downy brome near Richmond, UT. The study was started in 2017 and data was collected in May every year following treatment application.

		Desirable richness					
Treatments*	Rate	2018	2019	2020	2021	2022	μ Separation†
	g ai ha^{-1}	number of species					
Untreated	-	6	8	6	7	6	6 a
Indaziflam	102	6	6	6	6	6	6 abc
Propoxycarbazone	59	7	7	6	6	6	6 ab
Rimsulfuron	70	6	7	6	5	6	6 abc
Imazapic	175	7	7	6	7	5	6 a
Glyphosate	210	6	6	4	6	5	6 bc
Indaz + Propoxy	102 + 59	6	5	4	6	6	5 c
Indaz + Rimsulf	102 + 70	6	6	6	7	6	6 abc
Indaz + Imaz	102 + 175	6	7	6	6	7	7 a
Indaz + Glypho	102 + 210	5	6	5	5	5	5 c
Yearly average‡		6 a	6 a	5 b	6 ab	6 ab	

* All treatments included a non-ionic surfactant at 0.25% v/v.

† Values labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

‡ Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 2.23. Total plant richness as a response to the interaction of treatments by time from a study to control downy brome near Richmond, UT. The study was started in 2018 and data was collected in May every year following treatment application.

		Total plant richness[†]							
Treatments*	Rate	2019		2020		2021		2022	
	g ai ha^{-1}	number of species							
Untreated	-	11	a-f	11	a-d	11	a-f	10	a-h
Indaziflam	102	9	b-h	9	b-h	8	gh	8	gh
Propoxycarbazone	59	7	h	9	b-h	12	ab	12	ab
Rimsulfuron	70	10	a-g	11	abc	12	ab	9	b-h
Imazapic	175	8	gh	9	d-h	10	a-g	10	a-g
Glyphosate	210	11	a-f	10	a-g	11	a-e	8	fgh
Indaz + Propoxy	102 + 59	9	b-h	10	a-h	8	e-h	10	a-g
Indaz + Rimsulf	102 + 70	9	d-h	9	c-h	8	gh	8	gh
Indaz + Imaz	102 + 175	11	a-f	12	a	7	h	9	d-h
Indaz + Glypho	102 + 210	8	gh	7	h	9	d-h	8	fgh
Yearly average		9		10		9		9	

* All treatments included a non-ionic surfactant at 0.25% v/v.

[†] Values labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 2.24. Invasive plant richness as a response to the interaction of treatments by time from a study to control downy brome near Richmond, UT. The study was started in 2018 and data was collected in May every year following treatment application.

		Invasive plant richness[†]							
Treatment*	Rate	2019		2020		2021		2022	
	g ai ha^{-1}	number of species							
Untreated	-	4	b-h	5	a-d	5	a-d	5	a-e
Indaziflam	102	3	c-h	4	b-h	2	gh	2	fgh
Propoxycarbazone	59	2	gh	4	a-f	5	a-d	6	ab
Rimsulfuron	70	4	b-h	5	abc	5	abc	5	a-d
Imazapic	175	3	d-h	3	c-h	4	a-f	5	a-d
Glyphosate	210	4	b-g	5	a-d	4	b-g	3	c-h
Indaz + Propoxy	102 + 59	4	b-h	4	b-g	3	c-h	3	d-h
Indaz + Rimsulf	102 + 70	3	c-h	4	b-h	3	c-h	2	gh
Indaz + Imaz	102 + 175	5	abc	6	a	2	h	3	d-h
Indaz + Glypho	102 + 210	3	d-h	3	e-h	3	c-h	3	c-h
Yearly average		3		4		4		4	

* All treatments included a non-ionic surfactant at 0.25% v/v.

[†] Values labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 2.25. Desirable plant richness as a response to treatments from a study to control downy brome near Richmond, UT. The study was started in 2018 and data was collected in May every year following treatment application.

		Desirable plant richness			
Treatments*	Rate	2019	2020	2021	2022
	g ai ha^{-1}	number of species			
Untreated	-	7	6	6	5
Indaziflam	102	6	5	6	6
Propoxycarbazone	59	5	5	7	6
Rimsulfuron	70	6	6	7	5
Imazapic	175	5	5	6	5
Glyphosate	210	7	6	7	5
Indaz + Propoxy	102 + 59	6	6	5	7
Indaz + Rimsulf	102 + 70	5	5	5	6
Indaz + Imaz	102 + 175	6	6	5	6
Indaz + Glypho	102 + 210	5	5	5	5
Yearly average		6	5	6	5

* All treatments included a non-ionic surfactant at 0.25% v/v.

Table 2.26. Total plant diversity as a response to treatments and time from a study to control downy brome near Richmond, UT. The study was started in 2017 and data was collected in May every year following treatment application.

		Total diversity					
Treatments*	Rate	2018	2019	2020	2021	2022	μ Separation†
	g ai ha^{-1}	Shannon Diversity Index					
Untreated	-	1.76	1.77	1.59	1.61	1.68	1.89 a
Indaziflam	102	1.57	1.61	1.37	1.44	1.55	1.85 b
Propoxycarbazone	59	1.94	1.90	1.64	1.60	1.72	1.92 a
Rimsulfuron	70	1.60	1.92	1.73	1.47	1.62	1.89 a
Imazapic	175	1.72	1.84	1.52	1.67	1.37	1.80 d
Glyphosate	210	1.65	1.77	1.46	1.49	1.42	1.75 f
Indaz + Propoxy	102 + 59	1.46	1.40	1.38	1.29	1.59	1.78 e
Indaz + Rimsulf	102 + 70	1.33	1.49	1.28	1.33	1.45	1.82 c
Indaz + Imaz	102 + 175	1.46	1.51	1.41	1.27	1.61	1.84 bc
Indaz + Glypho	102 + 210	1.36	1.24	1.14	0.96	1.35	1.60 g
Yearly average‡		1.59 ab	1.64 a	1.45 c	1.41 c	1.54 b	

* All treatments included a non-ionic surfactant at 0.25% v/v.

† Values labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

‡ Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 2.27. Total plant diversity as a response to time from a study to control downy brome near Richmond, UT. The study was started in 2018 and data was collected in May every year following treatment application.

		Total diversity			
Treatments*	Rate	2019	2020	2021	2022
	g ai ha^{-1}	——— Shannon Diversity Index ———			
Untreated	-	2.04	1.85	1.98	1.67
Indaziflam	102	1.76	1.63	1.89	1.69
Propoxycarbazone	59	1.76	1.85	2.01	1.76
Rimsulfuron	70	1.92	1.82	2.04	1.68
Imazapic	175	1.81	1.86	1.86	1.66
Glyphosate	210	1.91	1.76	1.78	1.38
Indaz + Propoxy	102 + 59	1.90	1.73	1.92	1.79
Indaz + Rimsulf	102 + 70	1.75	1.92	1.72	1.52
Indaz + Imaz	102 + 175	2.02	2.00	1.61	1.60
Indaz + Glypho	102 + 210	1.62	1.79	1.78	1.69
Yearly average‡		1.85 a	1.82 a	1.86 a	1.64 b

* All treatments included a non-ionic surfactant at 0.25% v/v.

‡ Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 2.28. Total plant evenness as a response to treatments and time from a study to control downy brome near Richmond, UT. The study was started in 2017 and data was collected in May every year following treatment application.

		Total evenness					
Treatments*	Rate	2018	2019	2020	2021	2022	μ Separation[†]
	g ai ha^{-1}	Pielou Evenness Index					
Untreated	-	0.76	0.68	0.74	0.68	0.71	0.71 ab
Indaziflam	102	0.71	0.72	0.66	0.63	0.66	0.68 bc
Propoxycarbazone	59	0.78	0.74	0.77	0.72	0.73	0.75 a
Rimsulfuron	70	0.67	0.74	0.70	0.65	0.68	0.69 bc
Imazapic	175	0.71	0.73	0.67	0.70	0.64	0.69 bc
Glyphosate	210	0.69	0.66	0.64	0.64	0.63	0.65 c
Indaz + Propoxy	102 + 59	0.70	0.64	0.69	0.60	0.70	0.67 c
Indaz + Rimsulf	102 + 70	0.65	0.69	0.63	0.61	0.64	0.64 c
Indaz + Imaz	102 + 175	0.69	0.66	0.64	0.59	0.67	0.65 c
Indaz + Glypho	102 + 210	0.65	0.57	0.58	0.48	0.68	0.59 d
Yearly average[‡]		0.70 a	0.68 a	0.67 a	0.63 b	0.67 a	

* All treatments included a non-ionic surfactant at 0.25% v/v

[†] Values labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

[‡] Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 2.29. Total plant evenness as a response to time from a study to control downy brome near Richmond, UT. The study was started in 2018 and data was collected in May every year following treatment application.

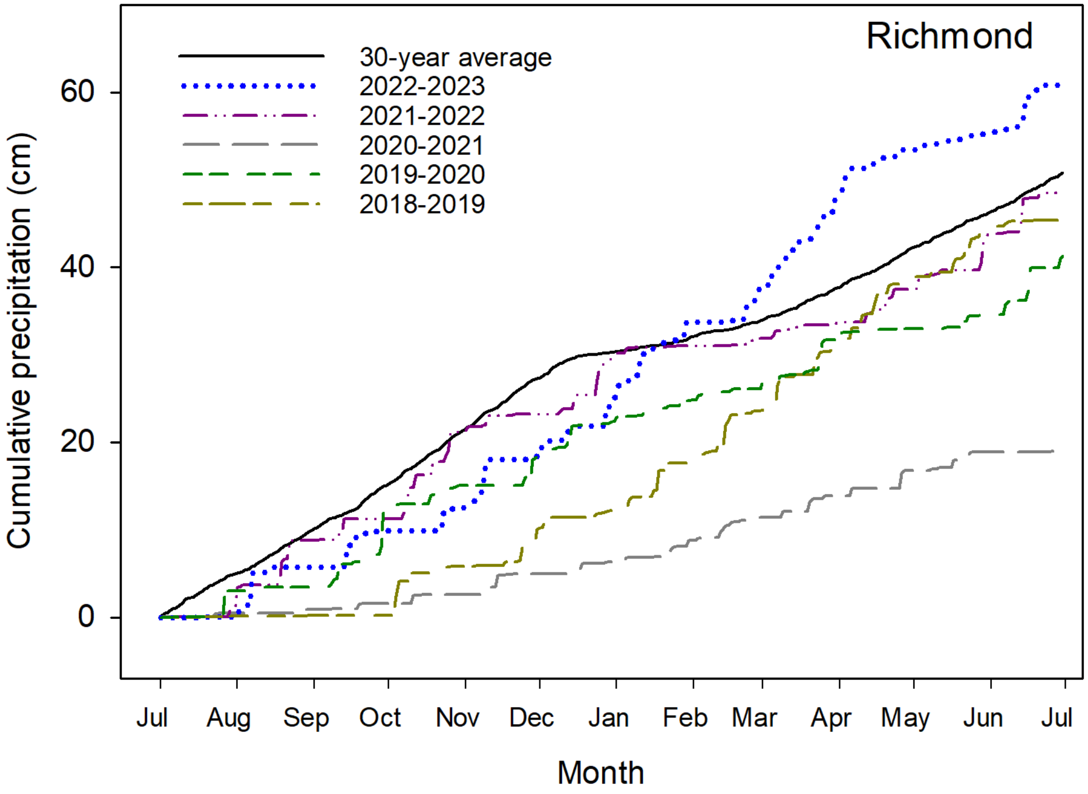
		Evenness			
Treatments*	Rate	2019	2020	2021	2022
	g ai ha^{-1}	Pielou Evenness Index			
Untreated	-	0.87	0.78	0.84	0.76
Indaziflam	102	0.80	0.74	0.92	0.84
Propoxycarbazone	59	0.93	0.85	0.82	0.72
Rimsulfuron	70	0.85	0.76	0.84	0.76
Imazapic	175	0.89	0.87	0.81	0.74
Glyphosate	210	0.81	0.76	0.76	0.66
Indaz + Propoxy	102 + 59	0.89	0.77	0.91	0.79
Indaz + Rimsulf	102 + 70	0.84	0.91	0.84	0.75
Indaz + Imaz	102 + 175	0.87	0.81	0.83	0.75
Indaz + Glypho	102 + 210	0.80	0.90	0.85	0.82
Yearly average‡		0.86 a	0.82 b	0.84 ab	0.76 c

* All treatments included a non-ionic surfactant at 0.25% v/v.

‡ Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Data Figure

Figure 2.1. Annual cumulative precipitation data for Richmond downy brome trial from 2018 to 2023 with 30-year average rainfall from 1993 to 2023, taken from the nearest NOAA weather station in Richmond, UT (NOAA 2023).



CHAPTER III

Effects Of Indaziflam-Inclusive Herbicide Mixtures On Highly Degraded, Ventenata Infested Ecosystems Multiple Years After Application

Abstract

Ventenata *(Ventenata dubia)* is an invasive annual grass found in many areas of the Western US; however, ventenata has yet to establish a prominent population within the state of Utah. There exists a high threat of the weed entering northern Utah from Idaho and Wyoming. Indaziflam, a recent addition to the herbicide market, is widely considered effective against ventenata (*Ventenata dubia)*; however, much of the herbicide's environmental impacts are still debated. Indaziflam works by preventing germination success in seedlings and has a soil activity of 3-5 years, longer than the soil persistence of most invasive annual grass seeds. Much of the recently published data testing indaziflam only looks at the first few years after application. This has led to a knowledge gap, as little is recorded about the effects of the herbicide in the long run. The goal of this study was to determine the environmental impacts of indaziflam applications 3 to 5 years post-application in a highly degraded ecosystem. A random, complete block design experiment with 12 different herbicide treatments was applied in 2017, and then repeated in 2018, to a degraded pasture in southern Cache Valley in Northern Utah. Line-point intercept transects were used to annually measure percent coverage of the different species found in each plot. This data was then used to calculate environmental metrics, such as cover for key species, functional groups, richness, diversity, and evenness. The study found that applications of indaziflam were correlated with decreased invasive

species cover and increased desirable species cover. The study also found no strong evidence of correlations between indaziflam application and decreased desirable richness. While indaziflam was correlated with decreases in plant diversity and evenness, such decreases also correlated with decreases in invasive annual grasses in the same plots. The study concludes that there is minimal evidence to suggest that indaziflam applications lead to long-term negative impacts on the desirable plant communities.

Introduction

Ventenata (*Ventenata dubia*) is an emerging invader that is prevalent throughout much of the north-western US, particularly in Washington, Oregon, Idaho, and Montana (Innes 2022, Wallace *et al.* 2015). While ventenata has limited distribution in the state of Utah, it is a weed of growing concern and is designated as a 1B State Noxious weed, meaning that eradication is a high priority (Lowry *et al.* 2017). Ventenata, in particular, has a very high seed production capability of upwards of 40,000 seeds per square meter per year (Beck 2014, Wallace *et al.* 2015), which is about 33% more than downy brome (*Bromus tectorum*) (Nesse and Ball 1994). Like many other invasive annual grasses, the seeds of ventenata tend to be short lived in the soil, persisting between 2-3 years (Bummer 2013, Prather 2019, Rinella *et al.* 2014).

Ventenata’s ability to quickly generate a high seed bank density provides many serious issues to land managers. The species has relatively high silica content, roughly 9% of its dry biomass, and it is completely unpalatable to grazing animals (Mangold *et al.* 2019).

When recent studies compared the ecological relationship of ventenata with fire, they found little evidence that fire was a significant driver in ventenata population. (Ridder *et al.* 2021, Watson *et al.* 2021).

Long term ventenata control has proven challenging using conventional chemical control methods, often requiring multiple applications to see any significant control (Bussan *et al*. 1999, Davies *et al*. 2019). Moreover, such strategies often come at a cost to ecological health metrics, such as diversity and richness (Harvey 2020, Koby *et* al. 2019, Rinella *et al.* 2014).

Indaziflam was first introduced to the market in 2010 by Bayer CropScience (US EPA 2010). Indaziflam works by inhibiting cellulose biosynthesis in germinating seedlings (Brabham *et al.* 2014). Researchers and land managers have found this mode of action to be effective against invasive annuals, and particularly, invasive annual grasses. This is, in part, due to indaziflam's 3 to 5 year soil activity (half-life > 150 days) (US EPA 2010), which can outlast the soil seed persistence of the invasive annual grasses.

Most studies that have investigated controlling invasive annual grasses using indaziflam typically look at the first two years of data. Unfortunately, this has led to a knowledge gap concerning the long-term effects of indaziflam applications and generated some concern regarding the herbicide.

The studies presented in this chapter is a continuation of research published in a previous MS Thesis (Buell 2021), adding an additional three years of observations to the original studies, the purpose of which was understand the ecological impacts of indaziflam and indaziflam-inclusive mixtures on ventenata infestations. The hypothesis for the initial research study, and maintained by this continuation, is that indaziflam and indaziflam-inclusive treatments will lead to reduced populations of ventenata without causing deleterious effects to the local ecosystem.

Methods and Materials

Field Study. The study site sits at the southern edge of the Cache Valley, near Mount Sterling, Utah (41º34'38.64" N, 111º54'35.01" W; 1601 m elevation). This site is a degraded pastureland actively used to graze cattle. This site is unique since it is moderately infested with ventenata (*Ventenata dubia),* along with weedy forbs like teasel (*Dipsacus fullonum*) and bull thistle (*Cirsium vulgare*). The first trial began at this site in 2017 and was repeated again adjacent to the first in 2018. Similar treatments, with 4 replications, were used in both iterations of the experiment (Table 3.1). In the 2017 trial, the aminopyralid + MSO, Quinclorac + MSO, and Imazapic + MSO were all applied in the spring, with the rest of the treatments being applied in the late fall, right before the ground froze. In the 2018 trial, Quinclorac was switched with an Indaziflam alone treatment, and all treatment timings were switch to early and late fall. All plots here measured 6 m by 9 m. All treatments were applied using a CO_2-pressurized backpack spray, calibrated to deliver 234 L/ha at 276 KPa and all treatment included a non-ionic surfactant at 0.25% v/v.

Data Collection. Cover data was collected once a year using line-point intercept transects through the center of each plot, data being taken every 15 cm, for a total of 60 data points. Data was converted to a percentage and then transformed using an arcsin(sqrt) transformation (Equation 3.1) to meet the assumptions of normality:

$$T_i = \sin^{-1}(\sqrt{(d_i)}) \quad \textbf{[3.1]}$$

T_i = transformed data at the i^{th} data point, d_i = i^{th} data point where $0 < d_i < 1$

The plant cover data was then used to calculate functional group cover (invasives vs. desirables), richness, diversity, and evenness as metrics of ecosystem health. Comprehensive lists of all desirable and invasive species identified throughout both repetitions of the study are recorded in tables 3.2 and 3.3, respectively.

Diversity and evenness were calculated using the Shannon Diversity Index (Equation 3.2) and Pielou Evenness Index (Equation 3.3), respectively, as expressed in Wu and Ding 2020 :

$$H' = -\sum_i (p_i * \ln(p_i)) \quad \textbf{[3.2]}$$

H' = Diversity Index, p_i = proportion of s made up of the i^{th} species

$$E = H' / \ln(s) \quad \textbf{[3.3]}$$

E = Evenness Index, H' = Diversity Index, s = Number of species

Specific species of interest were ventenata (*Ventenata dubia*), downy brome (*Bromus tectorum*), field bindweed (*Convolvulus arvensis*), Gray's lomatium (*Lomatium grayi*), western salsify (*Tragopogon dubius*), wild onion (*Allium canadense*.), and prickly lettuce (*Lactuca serriola*), as well as a combined category of the native western perennial grasses, predominately western wheatgrass (*Pascopyrum smithii*). Full lists off all desirable and invasive species can be found on Tables 3.2 and 3.3, respectively. Significance and mean separation were determined using a repeated measures analysis of variance (ANOVA)($\alpha = 0.05$) and a Fisher's LSD, respectively. All data organization and analyses were done using SAS 9.4 (2013). Daily precipitation data from 1993 to 2023 was also collected from a weather station set up in Wellsville, UT (41º39'257.6 N, 111º53'27.6" W; 1386 m elevation) (NOAA 2023).

Study Results

In some instances, analysis showed significant year by treatment interactions, but in other instances only the main effects of herbicide or year or both were significant. Tables 3.4 and 3.5 show all p-values from the ANOVA analyses for all the subsequent tables in runs 1 and 2, respectively.

Individual Species Cover

Ventenata. In the 2017 study, ventenata population cover data recorded from the site was noteworthy in 2021, since little to no ventenata was recorded in all the treatments (Table 3.6). This was likely caused by the extended drought conditions across the West. The ventenata cover was greatly impacted by the interaction between the effects of treatment and time. In 2018, all treatments that included indaziflam showed significantly lower ventenata cover than the untreated control, as well as the rimsulfuron-alone treatment. In 2019, all indaziflam-inclusive treatments, likewise, maintained a significant reduction of ventenata cover. No treatments significantly reduced ventenata cover compared to the untreated control in 2020, 2021, and 2022.

Ventenata cover data in the 2018 study followed a wholly different pattern. Similar to the 2017 study, the 2018 trial data found a significant interaction between the variables of treatment and time (Table 3.7) In 2018, all treatments with indaziflam (both 44 and 73 g ai ha^{-1}) showed reduction to near 0% cover. Rimsulfuron was the only other herbicide to significantly reduce ventenata cover during 2018. In 2019, the indaziflam-inclusive mixtures were the only treatments to significantly reduce ventenata cover. The indaziflam mixtures maintained ventenata cover to 6% or less, while cover in all other treatment plots, including the untreated control, averaged between 16 to 30%. Again, in

2021, almost all plots showed great reduction in ventenata cover, with cover between 0 and 3% for every treatment, including the untreated control.

Annual Bromes. In the 2017 study, data for the annual bromes (downy and Japanese) cover were influenced by the effects of time and herbicide treatment, but not by the interaction of the two (Table 3.8). One important note is that the untreated was the only treatment to start with a brome cover higher than 5%, at 17%. The next highest was the aminopyralid treatment at 4%. Treatment averages were significantly reduced from the intreated control in all treatments that included indaziflam mixed with another, more conventional herbicide. All other treatments were not significantly different from the untreated control. Average annual brome average cover by year started rather low at 2%, but started rising significantly in 2020, ending at 20% in 2022.

In the 2018 iteration of the study, annual brome cover was significantly influenced by the interaction between herbicide treatment and time (Table 3.9). In 2019, the only treatment not to significantly differ from the untreated control were the aminopyralid, imazapic, and imazapic + MSO treatments. In 2020, all treatment containing indaziflam, plus the treatment of imazapic + MSO led to reduced brome cover from the control. Like the other invasive annual grasses in this study, all populations of brome in this study dipped greatly in 2021 due to the extended drought, and thus, no treatments were significantly different from the control. In 2022, only the indaziflam-inclusive treatments resulting in reductions of brome cover from the control, while all other treatments did not.

Field bindweed. In the 2017 study, the data showed that bindweed cover was influenced by the main effects of the herbicide treatments and time, with no interaction between variables (Table 3.10). Regarding treatment averages, the indaziflam (73 g ai ha^{-1}), imazapic + MSO, and indaziflam + glyphosate were the only treatments to show significant loss of bindweed cover when compared the untreated control. Both the imazapic + MSO and indaziflam (73 g ai ha^{-1}) treatments had less than 1% bindweed cover in every year of the study. The indaziflam + imazapic + MSO was the only treatment to see average bindweed cover significantly higher than the untreated control; however, bindweed cover in plots treated with this treatment were consistently between 29 and 31%, except for in 2022, when bindweed cover is all plots was greatly reduced. Average annual bindweed cover started at 8 and 6% in 2018 and 2019, respectively, rose significantly to 12% in 2020 and 2021, and then fell back to the previous level at 3% in 2022.

In the 2018 study, bindweed population cover was only significantly affected by herbicide treatments (Table 3.11) Furthermore, all treatments were either equal to the untreated control or higher, as the untreated control averaged <1%. Treatments that were correlated to significantly higher bindweed cover when compared the untreated control were the indaziflam (44 g ai ha^{-1}), indaziflam (73 g ai ha^{-1}), indaziflam + imazapic, indaziflam + glyphosate, and indaziflam + rimsulfuron treatments.

Lomatium. In the 2017 study, lomatium cover was affected by the main effects of the treatments and time, but not from an interaction between them (Table 3.12). The treatment with the lowest average lomatium cover was the untreated control, with <1%. Treatments increasing lomatium cover compared to the untreated control were indaziflam + glyphosate, indaziflam + rimsulfuron, and indaziflam + imazapic + MSO, with 6, 5, and 7% cover, respectively.

In the 2018 iteration, lomatium cover was impacted by the effects of the interaction between herbicide treatments and time; however, it is important to note that lomatium cover was not present in any plots in 2022 (Table 3.13). In 2019, the imazapic + MSO treatment was the only treatment to reduce lomatium cover, while the indaziflam + glyphosate was the only treatment to increased lomatium cover. In 2020, the imazapic + MSO treatment was again the only treatment to lead to a reduction in lomatium cover, while the indaziflam (44 g ai ha^{-1}), indaziflam (73 g ai ha^{-1}), rimsulfuron, indaziflam + glyphosate, indaziflam + rimsulfuron, and indaziflam + imazapic + MSO treatments all led to increased lomatium cover when compared to the control for that year. No differences were detected in the 2021 and 2022 years from the untreated controls.

Western salsify. Western salsify populations from the 2017 study were inconsistent, as each treatment ranged from 0 to 5% cover every year (data not shown).

In the 2018 study, Western salsify population cover responded to the interaction of herbicide by year (data not shown). Aminopyralid and imazapic + MSO initially decreased cover in 2019 but did not differ from the untreated control from 2020 to 2022. Indaziflam (44 g ai ha-1), indaziflam (73 g ai ha-1), imazapic, indaziflam + imazapic, and indaziflam + imazapic + MSO all initially increased salsify cover compared to the untreated; however, none of these treatments were different from the untreated by 2022.

Prickly lettuce. In both iterations of the study, prickly lettuce population cover was inconsistent, as the species was nearly absent in 2022. (data no shown).

Wild onion. In the 2017 study, wild onion populations were influenced by the effects of time and herbicide treatments, with no significant interaction between the two (Table 3.14). For treatment averages, the untreated control was 0%, making it the lowest average of all the treatments. The plots treated with indaziflam-inclusive mixtures all rated significantly higher onion cover than the untreated control. All other treatments were not significantly different. Average annual wild onion cover had a high of 2% in 2018-2020 and 2022, and a significantly different low of 0% in 2021.

In the 2018 study, wild onion cover was affected by the interaction of time and herbicide treatment (Table 3.15). In 2019, the rimsulfuron-alone and indaziflam-inclusive treatments, save indaziflam (73 g ai ha^{-1}) and indaziflam + rimsulfuron, all led to significantly greater wild onion cover when compared to the untreated control of that year,. In 2020, only the indaziflam (73 g ai ha^{-1}) and indaziflam + glyphosate resulting in increased onion cover over the control. In 2021, no wild onion cover was recorded. In 2022, all indaziflam-inclusive treatments, save indaziflam (44 g ai ha^{-1}), led to increased onion cover over the control.

Desirable grasses. During the 2017 trial, desirable grass populations were affected by time (Table 3.16). Average annual desirable grass cover was highest in 2018 at 20% and declined significantly to 6% in 2019. In 2020 and subsequent years, desirable grass cover rose significantly and ranged from 10 to 14%, though it never returned to its initial level.

In the 2018 study, desirable grass cover was influenced by both the effects of time and herbicide treatment, but with no significant interaction between the variables (Table 3.17). Treatment averages that showed significantly greater desirable grass cover than the untreated control were the aminopyralid, indaziflam (44 g ai ha^{-1}), indaziflam (73 g ai ha^{-1}), rimsulfuron, indaziflam + rimsulfuron, and indaziflam + imazapic + MSO treatments.

Average annual desirable grass cover started at 10% in 2019 and rose significantly to 21% in 2020 and 26% in 2022.

Functional Group Cover

Invasive plant cover. In the 2017 study, invasive plant cover was significantly affected by the interaction between herbicide treatment and time (Table 3.18). Invasive plant cover in the untreated control ranged for 54% to 88% over the 5 years of the study. Its lowest point was in the 2021 year, where drought effect correlated with a significant decrease in invasive annual grasses cover (ventenata and annual bromes). During the first year of the study, all indaziflam-inclusive treatments, as well as the rimsulfuron alone treatment, showed significantly less invasive plant cover than the untreated control. In 2019, only the indaziflam + imazapic and indaziflam + glyphosate treatments showed significantly less invasive plant cover than the untreated control. In 2022, only the indaziflam + glyphosate treatment reduced invasive plant cover compared to the control. No differenced from the untreated controls were found in 2021 or 2022.

In the 2018 study, only time had significant impacts on invasive plant cover (Table 3.19). Average annual invasive plant cover was had a high of 36 and 42% in 2019 and 2020, fell significantly to 25% in 2021, and then rose back up to 41% in 2022.

Desirable plant cover. In the 2017 iteration of the study, desirable plant cover was affected by herbicide and treatment, but not by any interaction between the variables (Table 3.20). The only herbicide treatments to maintain the desirable species average cover significantly higher than the untreated control was the rimsulfuron-alone treatment. All other treatments were not significantly different from the untreated control. Average annual desirable plant cover started at 27 and 26% in 2018 and 2019, then rose significantly in 2020 to 34%. Average annual cover then fell to 10% in 2022.

Unlike to the 2017 data, the 2018 data for desirable species cover only showed an affect from time (Table 3.21). Desirable species cover was greater than 54% in all years except for 2021 when it declined to 43%.

Plant Community Metrics

Richness. During the 2017 study, total plant richness was only affected by time (Table 3.22). Average annual total richness started at 4 in 2018 and rose steady and significant in both 2019 and 2020, with richness score of 7 and 8 respectively. In 2022, average annual total richness fell to 5.

This same interaction was detected in the invasive plant functional group richness of the same study, with no differences found between any of the treatments and the untreated control (Table 3.23). In 2018, average annual invasive richness started at 2 in 2018, rose steady and significantly in both 2018 and 2019, to richness levels of 4 and 5 respectively. Average annual invasive plant richness then fell back down to 4 in 2022.

For the 2017 study, desirable plant richness was significantly impacted by the interaction between both the herbicide treatments and time (Table 3.24). In 2018, no treatments correlated with reductions in desirable plant richness when compared to the untreated control. In 201, only the indaziflam (73 g ai ha^{-1}), indaziflam + imazapic, and indaziflam + glyphosate treatments led to significant reductions from the control. In 2020, no treatments differed from the control. In 2021, the aminopyralid + MSO, indaziflam (73 g ai ha^{-1}), indaziflam + glyphosate, and indaziflam + rimsulfuron treatments led to significant loss of desirable plant richness when compared to the untreated control. In 2022, no treatments correlated with a loss of desirable plant richness when compared to the untreated control.

In the 2018 study, the total plant richness data found that both treatment and time had significant effects, but no interaction was found between these variables (Table 3.25). The only treatments to reduce the average total plant species richness compared to the untreated control were the aminopyralid, indaziflam + rimsulfuron, and indaziflam + imazapic + MSO treatments. Average annual total plant richness started at 9 in 2019, but fell significantly every year until 2021 and 2022, where it was measured at 7 in both years.

The invasive plant richness in the 2018 study was only influenced by the effects of time (Table 3.26). Average annual invasive species richness had a high of 4 in 2019-2020 and 2021, with a significantly different low of 3 in 2021.

Similarly, desirable plant richness was likewise only impacted by the effects of time (Table 3.27). Average annual desirable plant richness started with a high of 5 in 2019, but fell significantly to 4 in 2020, and then again in 2021 and 2022 to 3.

Plant Diversity. In the 2017 study, the diversity data showed a significant interaction between herbicide treatment and year (Table 3.28). In 2018, the treatments that resulted in reductions in diversity were the aminopyralid + MSO treatment and all treatments that included indaziflam mixed with another herbicide. In 2019, only the indaziflam (73 g ai ha^{-1}), imazapic, indaziflam + glyphosate, and indaziflam + rimsulfuron treatments resulted in a significant reduction in the diversity index when compared to the untreated control. No treatments in 2020, 2021, or 2022 correlated with significant reduction in diversity when compared to the untreated control of their respective years.

In the 2018 iteration of the study, the diversity data likewise was affected by the interaction between the herbicide treatments and time (Table 3.29). In 2019, the aminopyralid, indaziflam (73 g ai ha $^{-1}$), indaziflam + imazapic, indaziflam + glyphosate, and indaziflam + rimsulfuron treatments resulted in significant reductions in diversity from the untreated control. In 2020, only the indaziflam + rimsulfuron treatment showed a significant reduction in diversity from the untreated control. No treatments were significantly different from the untreated control in 2021. In 2022, only the imazapic treatment was significantly less than the untreated control.

Plant Species Evenness. Evenness in the 2017 study was significantly affected by an interaction between herbicide treatment and time (Table 3.30). In 2018, all indaziflam-inclusive treatments, save indaziflam + rimsulfuron, showed a significant reduction in evenness from the untreated control; however, in 2019, all indaziflam-inclusive treatments had equal, or significantly higher, evenness scores when compared to the untreated control. Imazapic treatments did correlate with significant reductions in evenness in 2019. No significant differences were found between any of the treatments and the untreated control of their respective years from 2020 to 2022.

In the 2018 study, evenness was only influenced by time (Table 3.31). Average annual evenness scores were not significantly different from the 2019 to 2020; 0.78 to 0.79, respectively. There was a significant decrease in evenness in 2021, to a low of 0.67 points; however, evenness score returned to 0.74 points in 2022.

Discussion

Precipitation. When the main effect of time was prevalent as a factor of plant cover, it is likely that precipitation was the major driving force behind that. Figure 3.1 shows the annual precipitation for each growing year (July to June) for every year of the study, as well as a 30-year accumulative average. In many of the species, a drop in cover is often noted at the end of the 2020-2021 growing season, when precipitation was at its lowest. This is almost always followed by a recovery in 2022, as precipitation increased to near that of the 30-year average.

This pattern is especially prevalent in this study as the invasive annuals that plagued the degraded landscape were particularly sensitive to precipitation levels. Ventenata was almost completely absent from the study site in 2021 due to the extreme drought conditions experienced in the 2020-2021 growing year, in both study iterations. This shows that, unlike many naturalized species, ventenata may not fully adapted for drought-prone regions of Utah. Further research will be needed to better understand the relationship between ventenata and Utah's drought cycles.

Treatment effects on invasive annual grasses. One of the unique aspects of this study is its inclusive of ventenata as a species of interest. The Utah Noxious Weed Act classifies ventenata as a Class1B weed, or "[a] declared noxious and invasive weeds that [is] known to exist in the state in very limited populations and pose a serious threat to the state and should be considered as a very high priority" (Lowry *et al.* 2017).

In the 2017 study, indaziflam applications, especially when mixed another herbicide, provided significant control of ventenata during the first two years of the study when compared to the untreated control, aminopyralid, imazapic, and glyphosate;

however, these effects were lost in the latter half of the study. There was likely some premature degradation of the herbicide in these plots, as the 2018 iteration of the study showed indaziflam to highly effective on ventenata for all 4 years of that study.

The indaziflam applications in the 2017 study showed the herbicide to control annual brome populations, keeping them below 10% cover, for at least the first 4 years of the study. By the fifth year, brome populations had begun to rise as the herbicide degraded. The rate at which these populations grew in the final year of the study suggests that in these degraded landscapes, eliminating brome germination for 4 years might not be enough for long term reclamation. In the 2018 study, indaziflam applications showed a near complete control of annual bromes for the entirety of the study.

Treatment effects on invasive forbs. The three main forbs monitored in this study were bindweed, salsify, and prickly lettuce. Bindweed cover showed no correlation with indaziflam applications, a finding also found by Hansen *et al.* 2016. No correlations were noted with the annual prickly lettuce, nor the biennial salsify, though the data was confounded by consistent, low populations counts.

Treatment effects on desirable grasses. The data did not show a negative correlation between desirable grass cover and indaziflam applications. The 2018 study did suggest that applications of imazapic and glyphosate, both alone and mixed with indaziflam might have a negative effect on desirable grass cover.

Treatment effects in desirable forbs. Wild onion and lomatium were the two desirable forbs monitored over the course of this study. Forbs did not make up a sizable portion of the plant cover at this site, and in drought conditions, many forb species were not consistent present through the entirety of the study. The 2018 study data for wild onion did suggest that indaziflam may be linked to increased cover. This is likely due to the herbicide suppressing competition for invasive annual grasses.

Treatment effect on richness. The 2017 study did not show any significant changes in richness from the untreated control in total or invasive functional groups, nor was there long-term consistent reductions in the desirable functional group. The 2018 study found a negative correlation between aminopyralid and some indaziflam mixtures and reductions in total richness scores; however, neither the invasive nor desirable functional group richness score show this same trend. It is noteworthy that aminopyralid did not provide any long-term control for ventenata. There is almost no evidence to suggest that indaziflam application are any negative, long-term effects on richness in degraded landscapes when compared to the untreated controls or other conventional herbicides.

Treatment effect on diversity and evenness. Plant diversity in the 2017 study found that all treatments containing indaziflam did cause a significant reduction in diversity in the first two years after application; however, diversity measurements were not significantly lower than the untreated control in any year after that. In the 2018 study, none of the treatments that contained indaziflam correlated with significant decreases in average diversity after the second year of the study.

Regarding evenness in the 2017 study, several treatments, including the high rate indaziflam treatments saw a significant decreases in the first year after application, but no treatments were significantly lower than the untreated by the third year of the study. In the 2018 study, there was no correlation between indaziflam treatments and reduction in evenness.

The data here not only supports the hypothesis that indaziflam does not have any negative long-term effects that might be deleterious to the ecosystem, but also that it is as ecologically safe as many of the other conventional herbicides current on the market today.

Management Implications. The treatments regime of this study was very similar to that of Koby *et al.* 2019, though their study was conducted in a highly degraded landscape with less 25% cover of desirable grasses and lasted 2-3 years long. In Koby *et al.* 2019, they claimed to have been able to achieve between 10 and 30 percentage points in the growth of desirable perennial grass cover in plots treated with indaziflam (73 g ai ha^{-1}) mixed with glyphosate or rimsulfuron in just 16 months. Their treatments were applied in early February and March and did not include any stand-alone indaziflam mixtures. Almost all treatments in this study were applied in the early to late fall. In both cases, the desirable perennial grasses would have been dormant, while the invasive annual grasses would have been active. Both studies had measurements taken in the spring, and such be comparable to a degree.

The 2017 study was unable to produce similar results 6 month and 18 months after treatment. The study's indaziflam + glyphosate mixture saw a loss of 20 percentage points during the first and second measurements of the study. That gap had narrowed to 17 percentage points by the end of the study. Similarly, the study also saw 10 percentage point decrease between the first two measurements in plots treated with indaziflam + rimsulfuron. The untreated in the study lost 8 percentage points between the first two measurement; but returned to net 0 by the end of the study. None of the treatment averages for this study were different than that of the untreated control.

The 2018 study, in the treatments saw a +7, +16 and +14 percentage points changes in the indaziflam + glyphosate, indaziflam + rimsulfuron, and untreated plots from 2019 to 2020. After 4 years, those same plots saw a net change of +13, +20, and +17 percentage points.

An important characteristic of the Koby *et al.* 2019 data is that in both locations of their study, their indaziflam treatments resulted in the growth of perennial grass cover, even though the perennial grass cover decreased in the untreated plots of both iterations of their study. This study was unable to fully confirm their findings, not only suggesting that indaziflam is not correlated decreases in the perennial grass cover in highly degraded fields, but rather that perennial grass cover would decrease no more than it would if it were untreated. That being stated, there is evidence that reductions in competition pressure from annual grasses due to indaziflam applications does promote perennial grass cover increases in highly degraded fields when the untreated grasses were also prone to increases.

While the results of Koby *et al.* 2019 may be realistic under favorable condition, this study suggests that land managers should not have such high expectations as to hope for a 30-percentage-point increase in their landscape's perennial grass cover without additional restoration practices, especially if that landscape is highly degraded. However, like that study, this study further supports that indaziflam is a valuable tool and should be integrated with current invasive annual grasses management practices as it is as ecologically safe as many of the herbicide currently used across the western US. Further studies will be needed to determine the proper correlations between indaziflam-inclusive applications and perennial grass growth over time.

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Data Tables

Table 3.1. Treatments applied to control ventenata in a highly degraded plant community in 2017 and 2018 near Mt. Sterling, UT.

2017 Trial			2018 Trial		
Treatment*	Rate	Timing	Treatment*	Rate	Timing
	g ai ha^{-1}			g ai ha^{-1}	
Untreated	-	-	Untreated	-	-
Aminopyralid + MSO	123 + 1%	Spring	Aminopyralid	123	Early fall
Quinclorac + MSO	44 + 1%	Spring	Indaziflam	44	Early fall
Imazapic + MSO	105 + 1%	Spring	Imazapic + MSO	105	Early fall
Indaziflam	73	Early fall	Indaziflam	73	Early fall
Imazapic	175	Late fall	Imazapic	175	Late fall
Glyphosate	210	Late fall	Glyphosate	210	Late fall
Rimsulfuron	52.5	Late fall	Rimsulfuron	52.5	Late fall
Indaz + Imaz	73 + 175	Late fall	Indaz + Imaz	73 + 175	Late fall
Indaz + Glypho	73 + 210	Late fall	Indaz + Glypho	73 + 210	Late fall
Indaz + Rimsulf	73 + 52.5	Late fall	Indaz + Rimsulf	73 + 52.5	Late fall
Indaz + Imaz + MSO	73 + 105 + 1%	Late fall	Indaz + Imaz + MSO	73 + 105	Late fall

* All treatments included a non-ionic surfactant at 0.25% v/v, except those treatments containing MSO at 1.0% v/v.

Table 3.2. Comprehensive list of all desirable species identified in a study to control ventenata in 2017 and 2018 near Mt. Sterling, UT.

Desirable Species*			
Common Name	Scientific Name	Common Name	Scientific Name
Western Yarrow	*Achillea millifolium*	Sunflower	*Helianthis annua*
Wild Onion	*Allium canadenses*	Lomatium	*Lomatium* sp.
Fiddleneck	*Amsinckia menziesii*	Tarweed	*Madia* sp.
Sagebrush	*Artemisia tridentata*	Alfalfa	*Medicago sativa*
Hooker's Balsamroot	*Balsamorhiza hookeri*	Penstemon	*Penstemon* sp.
Arrowleaf	*Balsamorhiza sagittate*	Smooth Brome	*Bromus inermus*
Smooth Brome	*Bromus inermus*	Checker Mallow	*Sidalcea oregana*
Curlycup Gumweed	*Grindelia squarrosa*	Mule's Ear	*Wyethia mollis*

*Unable to fully identify: "long leaf", "native thistle", and "mountain trumpet."

Table 3.3. Comprehensive list of all invasive species identified in a study to control ventenata in 2017 and 2018 near Mt. Sterling, UT.

Invasive Species*			
Common Name	Scientific Name	Common Name	Scientific Name
Jointed Goatgrass	*Aegilops cylindrica*	Sweet Clover	*Melilotus* spp.
Stinkweed	*Artemisisa tilesii*	Fireweed	*Onagranceae* spp.
Aster	*Aster* sp.	Annual Bluegrass	*Poa annua*
Kochia	*Bassia scoparia*	Bulbous Bluegrass	*Poa bulbosa*
Japanese Brome	*Bromus japonica*	Prostrate knotweed	*Polygonum aviculare*
Downy Brome	*Bromus tectorum*	Sulfur Cinquefoil	*Pontilla recta*
Sedge	*Carex* sp.	Wild Rose	*Rosa acicularis*
Thistle	*Cirsium* spp.	Curly Dock	*Rumex crispus*
Field Bindweed	*Convolvulus arvenses*	Cutleaf vipergrass	*Scorzonera laciniata*
Tansy Mustard	*Descurainia pinnata*	Medusahead	*Taeniatherum caput-medusae*
Teasel	*Dipsacus fullonum*	Dandelion	*Taraxacum officinale*
Catchweed	*Galium aparine*	Salsify	*Tragopogon dubuis*
Dyer’s woad	*Isatis tinctora*	Ventenata	*Ventenata dubia*
Prickly Lettuce	*Lactuca serriola*	Speedwell	*Veronica* sp.

*Unable to fully identify: “Unknown knotweed”, “unknown purple”, “Spike”, and “Unknown TL.”

Table 3.4. P-values for treatment, year, and the treatment by year interaction for the response variables for tables produced from data collected from a study to control ventenata in near Mt. Sterling, UT. The study was started in 2017.

	Sources of Variation		
Table	Treatment	Year	Treatment: Year
3.6 - Ventenata	<0.01*	<0.01*	<0.01*
3.8 – Annual bromes	<0.01*	<0.01*	0.99
3.10- Field bindweed	<0.01*	<0.01*	0.99
3.12 - Gray’s lomatium	<0.01*	<0.01*	0.83
Western salsify (not shown)	0.37	<0.01	0.04*
Prickly lettuce (not shown)	0.06	<0.01*	<0.01*
3.14 – Wild onion	<0.01*	<0.01*	0.07
3.16 – Desirable grasses	0.07	<0.01*	0.96
3.18 – Invasive cover	<0.01*	<0.01*	<0.01*
3.20 - Desirable cover	0.05*	<0.01*	<0.01*
3.22 – Total richness	0.42	<0.01*	0.10
3.24 - Invasive richness	0.59	<0.01*	0.13
3.26 - Desirable richness	0.13	<0.01*	0.03*
3.28 - Diversity	0.81	<0.01*	<0.01*
3.30 - Evenness	0.82	<0.01*	<0.01*

*P-value less than 0.05

Table 3.5. P-values for treatment, year, and the treatment by year interaction for the response variables for tables produced from data collected from a study to control ventenata in near Mt. Sterling, UT. The study was started in 2018.

	Sources of Variation		
Table	Treatment	Year	Treatment: Year
3.7 - Ventenata	<0.01*	<0.01*	<0.01*
3.9 – Annual bromes	<0.01*	<0.01*	<0.01*
3.11- Field bindweed	<0.01*	0.40	0.99
3.13 - Gray’s lomatium	<0.01*	<0.01*	<0.01*
Western salsify (not shown)	<0.01*	<0.01*	0.03*
Prickly lettuce (not shown)	<0.01*	0.03*	<0.01*
3.15 – Wild onion	<0.01*	<0.01*	<0.01*
3.17 – Desirable grasses	<0.01*	<0.01*	0.45
3.19 – Invasive cover	0.06	<0.01*	0.75
3.21 - Desirable cover	0.07	<0.01*	0.99
3.23 – Total richness	<0.01*	<0.01*	0.08
3.25 - Invasive richness	0.07	0.02*	0.17
3.27 - Desirable richness	0.07	<0.01*	0.99
3.29 - Diversity	0.07	<0.01*	<0.01*
3.31 - Evenness	0.41	<0.01*	0.06

*P-value less than 0.05.

Table 3.6. *Ventenata dubia* cover in response to the interaction of treatments and time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2017 and data was collected in May every year following treatment application.

			Ventenata dubia (ventenata) cover†				
Treatment*	Rate	Timing	2018	2019	2020	2021	2022
	g ai ha^{-1}		%				
Untreated	-	-	35 c-j	57 a-e	14 j-r	1 rs	37 d-j
Aminopyralid + MSO	123 + 1%	Spring	66 abc	73 ab	22 g-n	0 rs	38 c-j
Quinclorac + MSO	44 + 1%	Spring	46 b-h	60 a-d	18 i-q	1 rs	22 g-o
Imazapic + MSO	105 + 1%	Spring	25 g-m	53 b-g	18 h-q	3 o-s	37 d-k
Indaziflam	73	Early fall	0 rs	18 j-r	29 e-l	3 p-s	31 e-l
Imazapic	175	Late fall	27 f-l	79 a	27 e-l	3 p-s	33 d-j
Glyphosate	210	Late fall	43 b-i	72 ab	31 d-k	4 n-s	57 a-f
Rimsulfuron	52.5	Late fall	1 rs	61 a-d	18 g-p	0 s	44 b-i
Indaz + Imaz	73 + 175	Late fall	0 s	11 l-s	28 g-n	8 m-s	37 d-j
Indaz + Glypho	73 + 210	Late fall	0 s	14 j-r	15 j-r	1 rs	33 d-k
Indaz + Rimsulf	73 + 52.5	Late fall	0 s	21 h-q	28 g-m	1 qrs	26 g-m
Indaz + Imaz + MSO	73 + 105 + 1%	Late fall	0 s	12 k-s	18 j-r	5 o-s	31 g-m
Yearly average			20	44	22	3	35

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

† Values labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 3.7. *Ventenata dubia* cover in response to the interaction of treatment by time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2018 and data was collected in May every year following treatment application.

			Ventenata dubia (ventenata) cover[†]							
Treatments*	Rate	Timing	2019		2020		2021		2022	
	g ai ha^{-1}		%							
Untreated	-	-	28	a-f	9	hij	0	k	25	b-g
Aminopyralid	123	Early fall	47	a	16	ghi	3	jk	31	a-e
Indaziflam	44	Early fall	1	jk	0	k	0	k	3	ijk
Imazapic + MSO	105	Early fall	14	fgh	18	e-h	1	jk	30	a-e
Indaziflam	73	Early fall	0	k	0	k	0	k	3	jk
Imazapic	175	Late fall	36	abc	24	b-g	0	k	28	c-h
Glyphosate	210	Late fall	36	ab	34	a-d	2	jk	38	ab
Rimsulfuron	52.5	Late fall	2	jk	17	d-h	0	k	16	e-h
Indaz + Imaz	73 + 175	Late fall	0	k	1	jk	1	jk	6	jk
Indaz + Glypho	73 + 210	Late fall	0	k	0	k	1	jk	2	jk
Indaz + Rimsulf	73 + 52.5	Late fall	0	k	0	k	0	k	1	jk
Indaz + Imaz + MSO	73 + 105	Late fall	0	k	0	k	0	k	1	jk
Yearly average			14		10		1		15	

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

[†] Values labeled with the same letter are not significantly different according to Fisher's LSD at $\alpha = 0.05$.

Table 3.8. *Bromus tectorum* and *B. japonica* cover in response to treatment and time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2017 and data was collected in May every year following treatment application.

			Annual brome (downy and Japanese) cover					
Treatments*	Rate	Timing	2018	2019	2020	2021	2022	μ Separation[†]
	g ai ha^{-1}		%					
Untreated	-	-	17	7	16	3	29	14 a
Aminopyralid + MSO	123 + 1%	Spring	0	2	12	5	28	9 abc
Quinclorac + MSO	44 + 1%	Spring	0	0	12	6	33	10 a-d
Imazapic + MSO	105 + 1%	Spring	4	4	16	7	36	14 ab
Indaziflam	73	Early fall	0	1	7	7	23	8 a-d
Imazapic	175	Late fall	0	0	9	13	21	9 a-d
Glyphosate	210	Late fall	4	1	8	3	22	7 a-e
Rimsulfuron	52.5	Late fall	3	0	10	2	15	6 b-e
Indaz + Imaz	73 + 175	Late fall	0	0	1	0	18	4 cde
Indaz + Glypho	73 + 210	Late fall	0	1	3	1	3	2 de
Indaz + Rimsulf	73 + 52.5	Late fall	0	0	2	2	8	2 de
Indaz + Imaz + MSO	73 + 105	Late fall	0	0	0	0	10	2 e
Yearly average[‡]			2 c	2 c	8 b	4 bc	20 a	

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

[†] Values under this header labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

[‡] Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 3.9. *Bromus tectorum* and *B. japonica* cover in response to the interaction of treatment by time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2018 and data was collected in May every year following treatment application.

			Annual brome (downy and Japanese) cover†							
Treatments*	Rate	Timing	2019		2020		2021		2022	
	g ai ha^{-1}		%							
Untreated	-	-	13	c-g	26	bcd	3	i-l	35	ab
Aminopyralid	123	Early fall	7	f-k	15	c-f	1	jkl	24	bcd
Indaziflam	44	Early fall	2	i-l	1	jkl	0	kl	3	h-l
Imazapic + MSO	105	Early fall	9	e-i	10	f-j	1	kl	28	bc
Indaziflam	73	Early fall	1	jkl	0	kl	0	l	2	kl
Imazapic	175	Late fall	4	g-k	21	b-e	4	g-l	51	a
Glyphosate	210	Late fall	4	i-l	16	c-f	5	g-k	36	ab
Rimsulfuron	52.5	Late fall	2	i-l	11	d-h	4	i-l	45	a
Indaz + Imaz	73 + 175	Late fall	1	jkl	1	kl	0	l	2	jkl
Indaz + Glypho	73 + 210	Late fall	0	l	0	l	0	l	0	l
Indaz + Rimsulf	73 + 52.5	Late fall	0	l	0	l	0	l	0	l
Indaz + Imaz + MSO	73 + 105	Late fall	0	l	0	l	0	l	5	h-l
Yearly average			4		8		2		19	

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

† Values labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 3.10. *Convolvulus arvensis* cover in response to treatments and time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2017 and data was collected in May every year following treatment application.

			Convolvulus arvensis (field bindweed) cover					
Treatments*	Rate	Timing	2018	2019	2020	2021	2022	μ Separation†
	g ai ha^{-1}		%					
Untreated	-	-	13	9	25	23	3	15 b
Aminopyralid + MSO	123 + 1%	Spring	2	1	15	10	0	6 cd
Quinclorac + MSO	44 + 1%	Spring	1	2	15	12	3	7 bc
Imazapic + MSO	105 + 1%	Spring	0	0	0	1	0	0 d
Indaziflam	73	Early fall	0	0	1	0	0	0 d
Imazapic	175	Late fall	8	3	12	8	0	6 bc
Glyphosate	210	Late fall	12	5	13	16	1	9 bc
Rimsulfuron	52.5	Late fall	11	6	6	15	0	8 bc
Indaz + Imaz	73 + 175	Late fall	8	4	15	8	0	7 bc
Indaz + Glypho	73 + 210	Late fall	1	4	3	6	2	3 cd
Indaz + Rimsulf	73 + 52.5	Late fall	5	13	7	15	13	11 b
Indaz + Imaz + MSO	73 + 105	Late fall	29	29	31	31	9	26 a
Yearly average			8 b	6 b	12 a	12 a	3 b	

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

† Values under this header labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 3.11. *Convolvulus arvensis* cover in response to treatments from a study to control ventenata near Mt. Sterling, UT. The study was started in 2018 and data was collected in May every year following treatment application.

			Convolvulus arvensis (field bindweed) cover					
Treatments*	Rate	Timing	2019	2020	2021	2022	μ Separation†	
	g ai ha^{-1}		%					
Untreated	-	-	0	0	0	0	0	d
Aminopyralid	123	Early fall	0	0	3	0	1	d
Indaziflam	44	Early fall	7	10	13	3	8	ab
Imazapic + MSO	105	Early fall	3	2	6	0	3	cd
Indaziflam	73	Early fall	8	9	13	10	10	ab
Imazapic	175	Late fall	0	2	3	0	1	cd
Glyphosate	210	Late fall	1	5	7	0	3	cd
Rimsulfuron	52.5	Late fall	0	0	0	0	0	d
Indaz + Imaz	73 + 175	Late fall	3	6	10	6	6	bc
Indaz + Glypho	73 + 210	Late fall	2	3	9	6	5	bc
Indaz + Rimsulf	73 + 52.5	Late fall	15	13	15	22	16	a
Indaz + Imaz + MSO	73 + 105	Late fall	3	2	3	2	3	cd
Yearly average			4	4	7	4		

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

† Values under this header labeled with the same letter are not significantly different according to Fisher's LSD at $\alpha = 0.05$.

Table 3.12. *Lomatium grayi* cover in response to treatments and time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2017 and data was collected in May every year following treatment application.

			Lomatium grayi (Gray's lomatium) cover					
Treatments*	Rate	Timing	2018	2019	2020	2021	2022	μ Separation†
	g ai ha^{-1}		%					
Untreated	-	-	0	0	2	0	0	0 d
Aminopyralid + MSO	123 + 1%	Spring	0	1	2	0	0	1 cd
Quinclorac + MSO	44 + 1%	Spring	1	3	4	0	0	2 bcd
Imazapic + MSO	105 + 1%	Spring	3	0	1	0	0	1 d
Indaziflam	73	Early fall	5	3	9	0	2	4 a-d
Imazapic	175	Late fall	1	0	3	0	0	1 d
Glyphosate	210	Late fall	1	1	7	0	0	2 bcd
Rimsulfuron	52.5	Late fall	3	3	6	0	0	3 bcd
Indaz + Imaz	73 + 175	Late fall	0	1	12	0	5	4 bcd
Indaz + Glypho	73 + 210	Late fall	0	5	16	0	10	6 ab
Indaz + Rimsulf	73 + 52.5	Late fall	4	5	7	0	8	5 abc
Indaz + Imaz + MSO	73 + 105	Late fall	3	4	13	1	12	7 a
Yearly average			2 bc	2 b	7 a	0 c	3 b	

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

† Values under this header labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 3.13. *Lomatium grayi* cover in response to the interaction of treatments by time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2018 and data was collected in May every year following treatment application.

			Lomatium grayi (Gray's lomatium) cover							
Treatments*	Rate	Timing	2019		2020		2021		2022	
	g ai ha^{-1}		%							
Untreated	-	-	5	f-i	5	fg	1	kl	0	l
Aminopyralid	123	Early fall	2	g-k	5	f-j	0	l	0	l
Indaziflam	44	Early fall	6	fgh	16	a-d	1	jkl	0	l
Imazapic + MSO	105	Early fall	0	l	0	kl	0	l	0	l
Indaziflam	73	Early fall	11	b-f	20	ab	1	i-l	0	l
Imazapic	175	Late fall	1	h-l	3	g-l	0	kl	0	l
Glyphosate	210	Late fall	5	f-j	3	g-k	1	jkl	0	l
Rimsulfuron	52.5	Late fall	9	def	15	a-e	0	kl	0	l
Indaz + Imaz	73 + 175	Late fall	2	g-l	10	c-f	1	kl	0	l
Indaz + Glypho	73 + 210	Late fall	15	a-e	25	a	2	jkl	0	l
Indaz + Rimsulf	73 + 52.5	Late fall	11	b-f	21	abc	1	kl	0	l
Indaz + Imaz + MSO	73 + 105	Late fall	5	efg	15	b-e	3	g-l	0	l
Yearly average‡			6		11		1		0	

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

† Values labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

‡ Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 3.14. *Allium canadense* cover in response to treatments and time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2017 and data was collected in May every year following treatment application.

			Allium canadense (wild onion) cover						
Treatments*	Rate	Timing	2018	2019	2020	2021	2022	μ Separation[†]	
	g ai ha^{-1}		%						
Untreated	-	-	0	0	0	0	0	0	d
Aminopyralid + MSO	123 + 1%	Spring	0	1	0	0	0	0	cd
Quinclorac + MSO	44 + 1%	Spring	0	1	1	0	0	1	cd
Imazapic + MSO	105 + 1%	Spring	3	0	3	0	0	1	cd
Indaziflam	73	Early fall	2	7	5	0	3	3	a
Imazapic	175	Late fall	4	0	1	0	1	1	cd
Glyphosate	210	Late fall	2	0	0	0	0	1	cd
Rimsulfuron	52.5	Late fall	2	0	1	0	0	1	cd
Indaz + Imaz	73 + 175	Late fall	2	4	4	0	4	3	ab
Indaz + Glypho	73 + 210	Late fall	1	5	4	0	6	3	a
Indaz + Rimsulf	73 + 52.5	Late fall	1	0	3	0	3	1	bc
Indaz + Imaz + MSO	73 + 105	Late fall	2	6	3	1	4	3	a
Yearly average[‡]			2 a	2 a	2 a	0 b	2 a		

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

[†] Values under this header labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

[‡] Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 3.15. *Allium canadense* cover in response to the interaction of treatments by time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2018 and data was collected in May every year following treatment application.

			Allium canadense (wild onion) cover							
Treatments*	Rate	Timing	2019		2020		2021		2022	
	g ai ha^{-1}		%							
Untreated	-	-	3	f-j	2	g-j	0	j	1	ij
Aminopyralid	123	Early fall	0	j	0	ij	0	j	0	j
Indaziflam	44	Early fall	11	abc	4	d-i	0	j	4	d-i
Imazapic + MSO	105	Early fall	2	g-j	2	f-j	0	j	0	j
Indaziflam	73	Early fall	6	b-g	6	b-f	0	j	8	a-d
Imazapic	175	Late fall	4	d-i	2	f-j	0	j	1	ij
Glyphosate	210	Late fall	8	a-d	1	hij	0	j	0	ij
Rimsulfuron	52.5	Late fall	2	hij	1	hij	0	j	1	ij
Indaz + Imaz	73 + 175	Late fall	12	abc	3	e-j	0	j	8	bcd
Indaz + Glypho	73 + 210	Late fall	16	a	7	b-e	0	j	10	abc
Indaz + Rimsulf	73 + 52.5	Late fall	5	c-h	4	e-j	0	j	6	c-h
Indaz + Imaz + MSO	73 + 105	Late fall	13	ab	6	c-h	0	j	11	abc
Yearly average‡			7		3		0		4	

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

† Values labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

‡ Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 3.16. Desirable grasses cover in response to time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2017 and data was collected in May every year following treatment application.

			Desirable grasses cover				
Treatments*	Rate	Timing	2018	2019	2020	2021	2022
	g ai ha^{-1}		%				
Untreated	-	-	12	4	13	14	12
Aminopyralid + MSO	123 + 1%	Spring	16	5	14	15	11
Quinclorac + MSO	44 + 1%	Spring	23	8	19	14	22
Imazapic + MSO	105 + 1%	Spring	22	4	18	11	10
Indaziflam	73	Early fall	23	5	10	6	9
Imazapic	175	Late fall	13	2	16	11	19
Glyphosate	210	Late fall	11	4	8	5	3
Rimsulfuron	52.5	Late fall	34	10	25	10	15
Indaz + Imaz	73 + 175	Late fall	19	9	9	12	12
Indaz + Glypho	73 + 210	Late fall	30	10	18	8	12
Indaz + Rimsulf	73 + 52.5	Late fall	18	8	7	3	9
Indaz + Imaz + MSO	73 + 105	Late fall	21	9	10	7	11
Yearly average‡			20 a	6 c	14 b	10 b	12 b

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

‡ Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 3.17. Desirable grasses cover in response to treatment and time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2018 and data was collected in May every year following treatment application.

			Desirable grasses cover				
Treatments*	Rate	Timing	2019	2020	2021	2022	μ Separation[†]
	g ai ha^{-1}		%				
Untreated	-	-	3	16	11	20	13 cd
Aminopyralid	123	Early fall	11	22	26	26	21 ab
Indaziflam	44	Early fall	11	22	19	45	25 a
Imazapic + MSO	105	Early fall	9	22	16	17	16 abc
Indaziflam	73	Early fall	6	29	19	34	22 a
Imazapic	175	Late fall	5	13	11	9	10 d
Glyphosate	210	Late fall	7	19	10	14	13 bcd
Rimsulfuron	52.5	Late fall	20	30	32	16	25 a
Indaz + Imaz	73 + 175	Late fall	5	21	8	34	17 abc
Indaz + Glypho	73 + 210	Late fall	15	22	14	28	20 abc
Indaz + Rimsulf	73 + 52.5	Late fall	18	18	20	25	20 ab
Indaz + Imaz + MSO	73 + 105	Late fall	10	20	14	42	21 ab
Yearly Average[‡]			10 c	21 ab	17 b	26 a	

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

[†] Values under this header labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

[‡] Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 3.18. Invasive plant cover in response to the interaction of treatments by time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2017 and data was collected in May every year following treatment application.

			Invasive plant cover[†]									
Treatments*	Rate	Timing	2018		2019		2020		2021		2022	
	g ai ha^{-1}		%									
Untreated	-	-	73	a-g	80	a-d	74	a-f	50	f-l	48	f-l
Aminopyralid + MSO	123 + 1%	Spring	70	a-h	87	ab	76	a-f	52	d-l	51	d-l
Quinclorac + MSO	44 + 1%	Spring	51	e-l	80	a-e	60	c-j	50	f-l	68	a-g
Imazapic + MSO	105 + 1%	Spring	51	e-l	74	a-f	54	d-k	49	f-l	55	c-k
Indaziflam	73	Early fall	3	n	57	c-k	50	e-l	53	d-l	60	c-j
Imazapic	175	Late fall	56	c-k	90	a	63	b-i	53	d-l	48	f-m
Glyphosate	210	Late fall	71	a-g	83	abc	66	a-h	55	d-k	31	j-o
Rimsulfuron	52.5	Late fall	22	l-n	77	a-f	51	e-l	48	f-m	36	i-n
Indaz + Imaz	73 + 175	Late fall	21	m-n	41	h-n	66	a-h	48	f-m	47	f-m
Indaz + Glypho	73 + 210	Late fall	8	on	50	e-l	42	g-n	56	c-k	53	d-k
Indaz + Rimsulf	73 + 52.5	Late fall	15	non	59	c-j	63	b-i	50	e-l	54	c-k
Indaz + Imaz + MSO	73 + 105	Late fall	31	k-o	65	a-g	63	b-i	68	a-h	56	c-k
Yearly average[‡]			39		70		60		53		50	

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

[†] Values under this header labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 3.19. Invasive plant cover in response to time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2018 and data was collected in May every year following treatment application.

			Invasive plant cover			
Treatments*	Rate	Timing	2019	2020	2021	2022
	g ai ha^{-1}		%			
Untreated	-	-	47	44	23	39
Aminopyralid	123	Early fall	51	48	25	43
Indaziflam	44	Early fall	37	43	22	36
Imazapic + MSO	105	Early fall	31	62	26	41
Indaziflam	73	Early fall	36	34	30	41
Imazapic	175	Late fall	51	57	29	38
Glyphosate	210	Late fall	45	53	41	46
Rimsulfuron	52.5	Late fall	29	33	24	31
Indaz + Imaz	73 + 175	Late fall	39	43	22	42
Indaz + Glypho	73 + 210	Late fall	21	24	23	50
Indaz + Rimsulf	73 + 52.5	Late fall	21	33	24	53
Indaz + Imaz + MSO	73 + 105	Late fall	31	31	16	31
Yearly average[‡]			36 a	42 a	25 b	41 a

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

[‡] Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at $\alpha = 0.05$.

Table 3.20. Desirable plant cover in response to treatments and time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2017 and data was collected in May every year following treatment application.

			Desirable plant cover					
Treatments*	Rate	Timing	2018	2019	2020	2021	2022	μ Separation†
	g ai ha^{-1}					%		
Untreated	-	-	12	19	24	32	15	20 bcd
Aminopyralid + MSO	123 + 1%	Spring	16	13	19	26	9	17 d
Quinclorac + MSO	44 + 1%	Spring	27	19	35	25	11	24 a-d
Imazapic + MSO	105 + 1%	Spring	31	13	41	27	8	24 a-d
Indaziflam	73	Early fall	36	42	43	23	5	30 ab
Imazapic	175	Late fall	24	9	32	26	18	24 bcd
Glyphosate	210	Late fall	16	16	28	23	9	18 cd
Rimsulfuron	52.5	Late fall	52	23	39	28	21	33 a
Indaz + Imaz	73 + 175	Late fall	22	37	31	36	5	26 a-d
Indaz + Glypho	73 + 210	Late fall	31	48	48	19	8	31 ab
Indaz + Rimsulf	73 + 52.5	Late fall	36	40	31	31	9	30 abc
Indaz + Imaz + MSO	73 + 105	Late fall	27	32	33	17	8	30 bcd
Yearly average‡			27 ab	26 b	34 a	26 ab	10 c	

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

† Values under this header labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

‡ Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 3.21. Desirable plant cover in response to time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2018 and data was collected in May every year following treatment application.

			Desirable plant cover			
Treatments*	Rate	Timing	2019	2020	2021	2022
	g ai ha^{-1}		%			
Untreated	-	-	52	55	39	61
Aminopyralid	123	Early fall	49	51	44	57
Indaziflam	44	Early fall	54	56	48	63
Imazapic + MSO	105	Early fall	69	38	52	59
Indaziflam	73	Early fall	49	62	41	54
Imazapic	175	Late fall	49	43	36	63
Glyphosate	210	Late fall	54	47	23	54
Rimsulfuron	52.5	Late fall	52	64	51	69
Indaz + Imaz	73 + 175	Late fall	47	46	46	55
Indaz + Glypho	73 + 210	Late fall	57	64	29	46
Indaz + Rimsulf	73 + 52.5	Late fall	55	57	47	44
Indaz + Imaz + MSO	73 + 105	Late fall	58	63	56	69
Yearly average‡			54 a	54 a	43 b	58 a

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

‡ Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 3.22. Total plant species richness in response to time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2017 and data was collected in May every year following treatment application.

			Total richness				
Treatments*	Rate	Timing	2018	2019	2020	2021	2022
	g ai ha^{-1}		number of species				
Untreated	-	-	5	7	9	8	6
Aminopyralid + MSO	123 + 1%	Spring	4	7	8	9	7
Quinclorac + MSO	44 + 1%	Spring	4	8	9	7	5
Imazapic + MSO	105 + 1%	Spring	5	6	10	8	6
Indaziflam	73	Early fall	4	10	9	7	7
Imazapic	175	Late fall	6	5	9	7	6
Glyphosate	210	Late fall	6	6	8	9	6
Rimsulfuron	52.5	Late fall	4	6	8	7	6
Indaz + Imaz	73 + 175	Late fall	4	9	7	7	7
Indaz + Glypho	73 + 210	Late fall	4	10	10	7	8
Indaz + Rimsulf	73 + 52.5	Late fall	3	8	7	7	8
Indaz + Imaz + MSO	73 + 105	Late fall	4	7	8	9	7
Yearly average‡			4 d	7 b	8 a	8 ab	5 c

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

‡ Values in this row labeled with the same letter are not significantly different according to Fisher’s LSD at α = 0.05.

Table 3.23. Invasive plant richness in response to time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2017 and data was collected in May every year following treatment application.

			Invasive richness				
Treatments*	Rate	Timing	2018	2019	2020	2021	2022
	g ai ha^{-1}		number of species				
Untreated	-	-	3	5	5	4	4
Aminopyralid + MSO	123 + 1%	Spring	2	4	6	6	5
Quinclorac + MSO	44 + 1%	Spring	2	5	5	5	4
Imazapic + MSO	105 + 1%	Spring	3	4	6	5	4
Indaziflam	73	Early fall	2	6	5	5	5
Imazapic	175	Late fall	4	4	5	5	4
Glyphosate	210	Late fall	3	4	5	6	4
Rimsulfuron	52.5	Late fall	2	4	5	4	4
Indaz + Imaz	73 + 175	Late fall	2	5	5	5	4
Indaz + Glypho	73 + 210	Late fall	2	5	5	5	5
Indaz + Rimsulf	73 + 52.5	Late fall	1	5	4	5	5
Indaz + Imaz + MSO	73 + 105	Late fall	1	4	4	6	4
Yearly average‡			2 c	4 b	5 a	5 a	4 b

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

‡ Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 3.24. Desirable plant richness in response to the interaction of treatments and time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2017 and data was collected in May every year following treatment application.

			Desirable richness[†]				
Treatments*	Rate	Timing	2018	2019	2020	2021	2022
	g ai ha^{-1}		number of species				
Untreated	-	-	1 ijk	1 e-i	3 b-g	4 a-d	2 g-k
Aminopyralid + MSO	123 + 1%	Spring	1 ijk	2 e-i	2 f-k	2 e-i	2 jk
Quinclorac + MSO	44 + 1%	Spring	2 h-k	2 c-h	3 c-h	3 d-h	2 ijk
Imazapic + MSO	105 + 1%	Spring	3 f-j	2 e-i	4 a-d	3 c-h	2 ijk
Indaziflam	73	Early fall	3 f-j	3 ab	3 b-f	2 f-j	3 jk
Imazapic	175	Late fall	2 f-k	1 h-k	3 b-g	3 d-h	3 ijk
Glyphosate	210	Late fall	3 f-j	2 e-i	3 d-h	3 c-h	2 ijk
Rimsulfuron	52.5	Late fall	2 g-k	2 e-i	3 e-i	3 d-h	2 ijk
Indaz + Imaz	73 + 175	Late fall	2 h-k	3 ab	2 e-i	2 d-h	3 k
Indaz + Glypho	73 + 210	Late fall	2 g-k	3 a	4 abc	2 f-k	4 h-k
Indaz + Rimsulf	73 + 52.5	Late fall	2 g-k	3 a-e	3 e-i	2 e-i	3 jk
Indaz + Imaz + MSO	73 + 105	Late fall	3 f-j	2 b-g	4 b-f	3 c-h	3 jk
Yearly average			2	3	3	3	2

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

[†] Values labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 3.25. Total plant species richness in response to treatments and time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2018 and data was collected in May every year following treatment application.

			Total richness				
Treatments*	Rate	Timing	2019	2020	2021	2022	μ Separation[†]
	g ai ha^{-1}		number of species				
Untreated	-	-	12	9	8	7	9 a
Aminopyralid	123	Early fall	7	8	6	6	6 cd
Indaziflam	44	Early fall	11	9	6	9	9 ab
Imazapic + MSO	105	Early fall	10	9	8	7	8 ab
Indaziflam	73	Early fall	9	9	6	7	8 ab
Imazapic	175	Late fall	10	10	7	5	8 ab
Glyphosate	210	Late fall	10	8	8	7	8 ab
Rimsulfuron	52.5	Late fall	11	10	6	7	8 ab
Indaz + Imaz	73 + 175	Late fall	9	8	7	9	8 ab
Indaz + Glypho	73 + 210	Late fall	8	8	7	8	8 ab
Indaz + Rimsulf	73 + 52.5	Late fall	7	6	6	6	6 d
Indaz + Imaz + MSO	73 + 105	Late fall	9	7	6	8	8 bc
Yearly average[‡]			9 a	8 b	7 c	7 c	

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

[†] Values under this header labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

[‡] Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 3.26. Invasive species richness in response to time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2018 and data was collected in May every year following treatment application.

			Invasive richness			
Treatments*	Rate	Timing	2019	2020	2021	2022
	g ai ha^{-1}		number of species			
Untreated	-	-	5	5	4	4
Aminopyralid + MSO	123 + 1%	Early fall	2	4	3	3
Quinclorac + MSO	44 + 1%	Early fall	5	4	2	5
Imazapic + MSO	105 + 1%	Early fall	5	5	4	4
Indaziflam	73	Early fall	4	4	3	4
Imazapic	175	Late fall	4	5	3	2
Glyphosate	210	Late fall	5	4	4	4
Rimsulfuron	52.5	Late fall	5	5	3	4
Indaz + Imaz	73 + 175	Late fall	4	4	3	4
Indaz + Glypho	73 + 210	Late fall	3	4	4	5
Indaz + Rimsulf	73 + 52.5	Late fall	2	3	3	4
Indaz + Imaz + MSO	73 + 105	Late fall	4	3	3	5
Yearly average‡			4 a	4 a	3 b	4 a

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

‡ Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 3.27. Desirable species richness in response to time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2018 and data was collected in May every year following treatment application.

			Desirable richness			
Treatments*	Rate	Timing	2019	2020	2021	2022
	g ai ha^{-1}		number of species			
Untreated	-	-	7	5	4	4
Aminopyralid	123	Early fall	5	4	3	3
Indaziflam	44	Early fall	6	5	4	4
Imazapic + MSO	105	Early fall	5	4	4	3
Indaziflam	73	Early fall	6	5	3	3
Imazapic	175	Late fall	6	4	4	3
Glyphosate	210	Late fall	6	4	4	3
Rimsulfuron	52.5	Late fall	6	5	3	3
Indaz + Imaz	73 + 175	Late fall	6	5	4	5
Indaz + Glypho	73 + 210	Late fall	6	5	3	3
Indaz + Rimsulf	73 + 52.5	Late fall	5	4	3	3
Indaz + Imaz + MSO	73 + 105	Late fall	5	4	4	4
Yearly average[‡]			5 a	4 b	3 c	3 c

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

[‡] Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 3.28. Plant species diversity in response to the interaction of treatment by time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2017 and data was collected in May every year following treatment application.

			Diversity†									
Treatments*	Rate	Timing	2018		2019		2020		2021		2022	
	g ai ha^{-1}		Shannon Diversity Index									
Untreated	-	-	1.15	j-s	1.27	e-q	1.67	a-h	1.45	b-m	0.94	o-u
Aminopyralid + MSO	123 + 1%	Spring	0.69	tu	0.92	p-u	1.66	a-h	1.60	a-i	0.92	p-u
Quinclorac + MSO	44 + 1%	Spring	0.91	p-u	1.18	h-r	1.70	a-f	1.40	b-n	0.94	o-u
Imazapic + MSO	105 + 1%	Spring	1.24	h-q	0.93	p-u	1.81	abc	1.60	a-i	0.83	q-u
Indaziflam	73	Early fall	0.73	stu	1.83	ab	1.65	a-h	1.32	d-p	1.10	l-t
Imazapic	175	Late fall	1.29	d-p	0.76	r-u	1.65	a-h	1.52	a-l	1.05	m-u
Glyphosate	210	Late fall	1.26	f-q	0.88	p-u	1.69	a-g	1.55	a-k	0.63	u
Rimsulfuron	52.5	Late fall	1.09	l-t	1.16	i-s	1.59	a-j	1.32	d-p	0.90	p-u
Indaz + Imaz	73 + 175	Late fall	0.79	r-u	1.63	a-h	1.45	b-m	1.49	a-m	1.00	n-u
Indaz + Glypho	73 + 210	Late fall	0.63	u	1.93	a	1.71	a-e	1.30	d-p	1.25	g-q
Indaz + Rimsulf	73 + 52.5	Late fall	0.79	r-u	1.72	a-d	1.38	c-o	1.30	d-p	1.13	k-t
Indaz + Imaz + MSO	73 + 105	Late fall	0.70	stu	1.48	b-m	1.53	a-l	1.32	d-p	1.24	g-q
Yearly average			0.94		1.31		1.62		1.43		0.99	

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

† Values labeled with the same letter are not significantly different according to Fisher's LSD at $\alpha = 0.05$.

Table 3.29. Plant species diversity in response to the interaction of treatments by time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2018 and data was collected in May every year following treatment application.

			Diversity							
Treatment*	Rate	Timing	2019		2020		2021		2022	
	g ai ha^{-1}		Shannon Diversity Index							
Untreated	-	-	2.04	a	1.79	a-e	1.20	o-r	1.46	e-r
Aminopyralid	123	Early fall	1.41	g-r	1.62	c-l	1.19	pqr	1.41	h-r
Indaziflam	44	Early fall	1.98	ab	1.77	a-e	1.21	n-r	1.52	d-p
Imazapic + MSO	105	Early fall	1.85	a-d	1.66	b-j	1.39	i-r	1.40	h-r
Indaziflam	73	Early fall	1.65	b-k	1.62	c-l	1.20	o-r	1.53	d-o
Imazapic	175	Late fall	1.71	a-i	1.88	abc	1.24	m-r	0.80	s
Glyphosate	210	Late fall	1.76	a-f	1.65	b-k	1.29	l-r	1.30	l-r
Rimsulfuron	52.5	Late fall	1.74	a-h	1.76	a-f	1.29	l-r	1.32	k-r
Indaz + Imaz	73 + 175	Late fall	1.68	b-j	1.60	c-l	1.21	o-r	1.66	b-k
Indaz + Glypho	73 + 210	Late fall	1.54	c-n	1.55	c-m	1.16	qr	1.71	a-i
Indaz + Rimsulf	73 + 52.5	Late fall	1.36	j-r	1.44	f-r	1.14	r	1.48	e-q
Indaz + Imaz + MSO	73 + 105	Late fall	1.75	a-g	1.58	c-l	1.24	m-r	1.55	c-m
Yearly average‡			1.71		1.66		1.23		1.43	

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

‡ Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 3.30. Plant species evenness in response to the interaction of treatments by time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2017 and data was collected in May every year following treatment application.

			Evenness[†]									
Treatments*	Rate	Timing	2018		2019		2020		2021		2022	
	g ai ha^{-1}		Pielou Evenness Index									
Untreated	-	-	0.76	a-h	0.67	d-q	0.78	a-f	0.71	a-m	0.58	k-s
Aminopyralid + MSO	123 + 1%	Spring	0.60	h-s	0.49	rs	0.81	a-e	0.75	a-i	0.56	l-s
Quinclorac + MSO	44 + 1%	Spring	0.69	c-q	0.59	i-s	0.81	a-d	0.71	a-m	0.60	g-s
Imazapic + MSO	105 + 1%	Spring	0.77	a-f	0.54	o-s	0.79	a-f	0.77	a-g	0.55	m-s
Indaziflam	73	Early fall	0.52	qrs	0.81	a-d	0.76	a-i	0.67	d-q	0.67	d-q
Imazapic	175	Late fall	0.75	a-i	0.47	s	0.77	a-f	0.77	a-g	0.68	c-q
Glyphosate	210	Late fall	0.73	a-k	0.53	p-s	0.80	a-e	0.69	b-p	0.53	o-s
Rimsulfuron	52.5	Late fall	0.78	a-f	0.63	f-s	0.77	a-f	0.72	a-l	0.64	e-r
Indaz + Imaz	73 + 175	Late fall	0.58	j-s	0.74	a-k	0.74	a-j	0.75	a-i	0.63	f-s
Indaz + Glypho	73 + 210	Late fall	0.55	l-s	0.87	a	0.77	a-f	0.64	e-r	0.65	e-r
Indaz + Rimsulf	73 + 52.5	Late fall	0.67	c-q	0.84	abc	0.71	a-n	0.65	e-r	0.67	d-q
Indaz + Imaz + MSO	73 + 105	Late fall	0.54	n-s	0.86	ab	0.76	a-h	0.67	d-q	0.70	a-o
Yearly average			0.66		0.67		0.77		0.70		0.62	

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

[†] Values labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Table 3.31. Plant species evenness in response to time from a study to control ventenata near Mt. Sterling, UT. The study was started in 2018 and data was collected in May every year following treatment application.

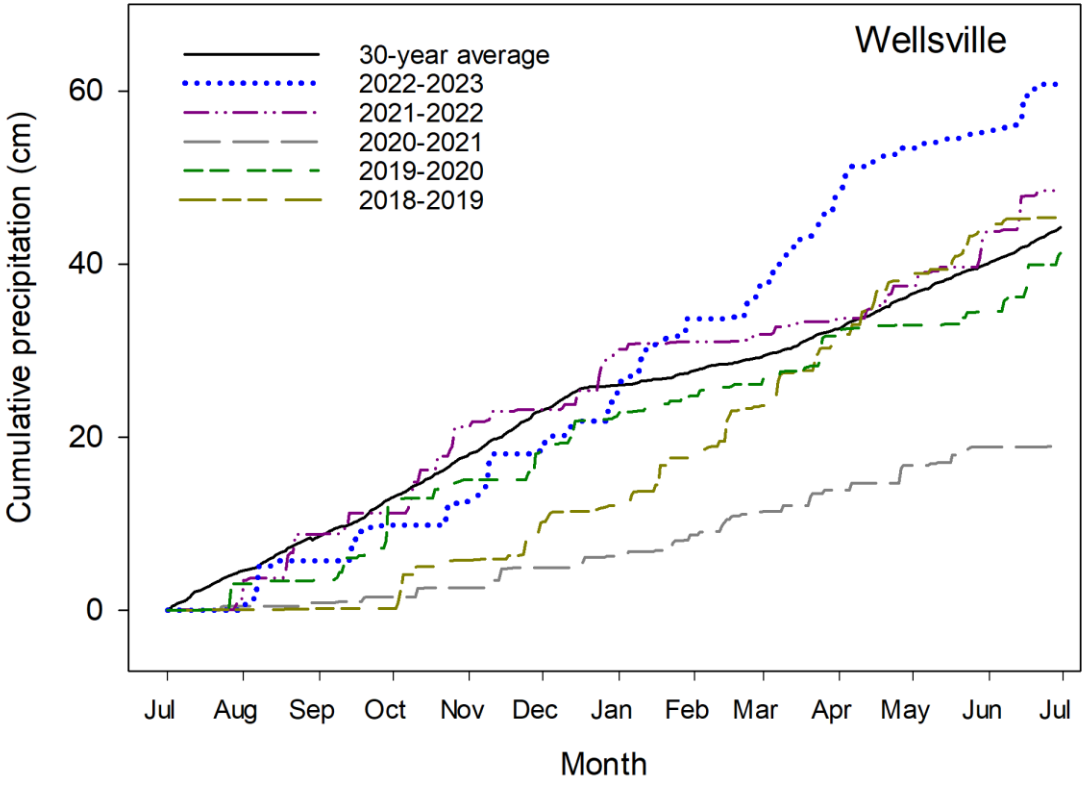
			Evenness			
Treatments*	Rate	Timing	2019	2020	2021	2022
	g ai ha^{-1}		———— Pielou Evenness Index			————
Untreated	-	-	0.83	0.80	0.60	0.76
Aminopyralid	123	Early fall	0.75	0.80	0.71	0.81
Indaziflam	44	Early fall	0.83	0.81	0.72	0.72
Imazapic + MSO	105	Early fall	0.81	0.76	0.69	0.73
Indaziflam	73	Early fall	0.75	0.76	0.67	0.77
Imazapic	175	Late fall	0.75	0.84	0.64	0.52
Glyphosate	210	Late fall	0.77	0.79	0.64	0.71
Rimsulfuron	52.5	Late fall	0.76	0.77	0.70	0.68
Indaz + Imaz	73 + 175	Late fall	0.77	0.76	0.65	0.78
Indaz + Glypho	73 + 210	Late fall	0.74	0.76	0.62	0.84
Indaz + Rimsulf	73 + 52.5	Late fall	0.73	0.79	0.69	0.82
Indaz + Imaz + MSO	73 + 105	Late fall	0.82	0.84	0.68	0.74
Yearly average‡			0.78 ab	0.79 a	0.67 c	0.74 b

* All treatments included a non-ionic surfactant at 0.25% v/v, except for those treatments containing MSO at 1.0% v/v.

‡ Values in this row labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

Data Figure

Figure 3.1. Annual cumulative precipitation data for the Mt. Sterling ventenata trial from 2018 to 2023 with 30-year average rainfall from 1993 to 2023, taken from the nearest NOAA weather station in Wellsville, UT (NOAA 2023).



CHAPTER IV

Furthering Seed-Based Revegetation Strategies For Indaziflam-Treated Areas

Abstract

One of the many difficulties of incorporating indaziflam in larger management plans is in considering how the herbicide, with its preemergence mode of action, interacts with revegetation seedings efforts. The studies presented herein explore several possible approaches that may allow for desirable seeds to successfully establish in areas treated with indaziflam. A field study, consisting of 4 replications of 12 treatments in randomized complete block design, was established in Fall 2021, with 4 desirable species planted in perpendicular rows though each plot. The treatments consisted of several different herbicides and application timings for a "multiple-entry" approach. Frame counts were used to collect seedling germination annually. A greenhouse study was established to explore the potential of chemical and physical barriers to protect seeding rows at the time of herbicide application. The study consisted of two runs of seven to eight treatments in which some treatments provided either a physical barrier to prevent herbicide from being applied to the row or a chemical barrier of activated charcoal to protect the seeding row at the time of herbicide application. The field study found that, when reseeded 12 MAT, germination counts in plots treated with indaziflam did not statistically differ from e the plots treated with other herbicide combinations or the untreated control. The greenhouse study found that seeding rows with a band of activated charcoal applied over the top have the potential to germinate and establish at densities similar to the untreated control. This

chapter concludes that it is possible to integrate indaziflam into revegetation and management plans, though further studies will be needed to refine the methodologies.

Introduction

The main challenge with revegetating Utah's rangeland is controlling invasive annual grasses long enough that the slower-growing, native perennial grasses can get established (Davies *et al.* 2017). This is incredibly difficult as invasive annual grasses, such as downy brome (*Bromus tectorum*), can have populations expansions of upwards of 14% a year (Bradley *et al.* 2018).

Having already invaded over 21 million acres, invasive annual grasses are a serious management concern in the Western US (Bradley *et al.* 2018). Many different management strategies have been tried and tested over the years, namely prescribed burns, grazing, mowing and chemical management (Davis *et al.* 2012, Monty *et al.* 2013, Williamson *et al.* 2019). While many land managers have become increasingly reliant on chemical management to control invasive annual grasses, many of the commonly used herbicide, namely rimsulfuron, glyphosate, and imazapic, do not have the soil persistence needed to effectively combat the invasive annual grasses (Morris *et al.* 2009; Sebastian *et al.* 2017; Terry *et al.* 2021).

In available in 2011, the herbicide indaziflam was introduced to the market originally for managing weeds in fruit, nut, and grape production (Bayer CropScience 2010, Parrish *et al.* 2009). Indaziflam is a cellulose biosynthesis inhibitor herbicide that, when applied to the top layer of a soil, functions as a seed germination inhibitor for up to 4 years (EPA 2010; Terry *et al*. 2021; Kestrel 2020). In the past few years, indazfilam's mode of action has caught the attention of many researchers and land managers in the west as a potential tool for controlling invasive annual grasses. These interests have since redoubled with a plethora of research confirming that indaziflam does indeed control invasive annual grasses such as downy brome (*Bromus tectorum*), ventenata (*Ventenata dubia*), and medusahead (*Taeniatherum caput-medusae*).

Despite these finding, incorporation of indaziflam into current management plans has proved to be difficult as indaziflam's mode of action also effectively prevents direct seeding. (Buell 2021, Landeen *et al.* 2023, Terry *et al.* 2021). Direct seeding is considered one of the most effective ways to revegetate a landscape, as it allows for control of species composition, reduced costs, larger revegetation areas, and minimal planning (Grossnickle and Ivetić 2017, Stanturf *et al*. 2014). Research is being done on multiple fronts to find a solution that would make indaziflam a practical option for land managers for use during revegetation efforts. The studies presented in this chapter were designed to consider several potential strategies for utilizing direct seeding with different herbicide applications, including indaziflam.

The first strategy of interest is the "multiple-entry" approach, which involves separating the herbicide applications across time, typically over 1-2 years, in order to mitigate their interaction with new seedings at the same site. (Buell 2021). While there is evidence the "multiple-entry" strategies show a positive correlation with restoration species densities, when compared to "single-entry" approach (when all herbicide applications and planting occur at the same time), these strategies are often more expensive and inconsistent. (Buell 2021, Davies et al. 2014, Landeen *et al.* 2023). The "multiple-entry" study in this chapter was designed to replicate and build off a study from a previously published MS Thesis (Buell 2021).

Several studies have also found success in using activated charcoal seed coatings (Clenet *et al.* 2019; Davies *et al.* 2017), though such technology is costly and not readily available for public or agency use. Greenhouse studies presented in this chapter seek to test an alternative method for applying activated charcoal to seeding rows, as well as explore the possibility of using temporary, physical barriers to protect seeding rows at the time of herbicide application.

Methods and Materials

Field Trial

The main field trial was conducted at Riverside, UT (41º48’14.” N, 112º10’30” W; 1330 m elevation). The area contained DeJarnet gravelly silt loam soil, which was stated to have 18.6% clay, 37.9% sand, and 43.5% silt, with <1% organic matter (USDA Soil Survey). An analysis by the Utah State University Analytical Laboratories found the soil to be a silt loam with high levels of organic matter, phosphorus, potassium, and low levels of sulfur. This is consistent with the intensive grazing that the site has experienced. The high levels of organic matter are likely a byproduct of animal waste from animals kept on the sight prior to being moved to rangeland for summer grazing. The site was heavily infested with medusahead (*Taeniatherum caput-medusae*) with intermittent sagebrush (*Artemisia tridentata*) and alfalfa (*Medicago sativa*).

This study contained 4 replications of 12 treatments (Table 4.1). Treatment applications occurred on May 25, 2021, for the Spring applications and November 16, 2021, for the Fall applications. Beyond the herbicide applications, each replication was seeded perpendicular to herbicide treatments on December 3rd, 2023, with randomized rows of small burnet (*Sanguisorba minor* var. Delar), Siberian wheatgrass (*Agropyron fragile* var. Vavilov II), intermediate wheatgrass (*Thinopyrum intermedium* var. Oahe), or thickspike wheatgrass (*Elymus lanceolatus* var. Critana) (Granite Seed & Erosion Control, 1697 W 2100 N, Lehi, UT, 84043), as well as an unplanted row. These seedings were then repeated 12 months later.

Seeding establishment data was collected in June of 2022 and May of 2023 and was measured using density counts using a 0.5 m^2 frame. Visual data was also collected for alfalfa injury and medusahead control at these same times. Count data was transformed using a simple square root transformation to meet the assumptions of normality (Equation 4.1), while percent data was transformed using a log transformation for the same reason (Equation 4.2).

$$T_i = \sqrt{(d_i)} \quad \textbf{[4.1]}$$

T_i = transformed data at the i^{th} data point, d_i = i^{th} data point

$$T_i = \ln(d_i) \quad \textbf{[4.2]}$$

T_i = transformed data at the i^{th} data point, d_i = i^{th} data point where $0 < d_i < 1$

This study was analyzed using a one-way analysis of variance (ANOVA) ($\alpha = 0.05$) for significance and a Fisher's LSD post-hoc test for mean separation.

Greenhouse Trials

Greenhouse studies sought to test the concept of protecting seedlings from herbicide injury by protecting the seed row by physically preventing the herbicide from being applied to a band over the seed row or applying a layer of activated charcoal over the seed row to bind the herbicide and prevent it from contacting the germinating seedlings. These studies were conducted at the Utah State University Research

Greenhouse in Logan, UT. Run 1 was conducted Jan 7- 27, 2023. Greenhouse conditions ranged from 24 C during the day to 19 C at night. Run 2 was conducted May 4-24, 2023. Greenhouse conditions for this run ranged from 27 C during the day to 19 C at night. Nibley silty clay loam soil was collected from a university farm in Nibley, UT and used in trials 1 and 2. The USDA reports the soil texture as 43.4% clay, 7.3% sand, and 49.3% silt, with <1% organic matter (USDA Soil Survey). An analysis by the Utah State University Analytical Laboratories found the soil to be a silt loam, with typical plant nutrients tending to be low.

Landmark© L1020 NCR Planting Trays with holes (Landmark Plastic, 1331 Kelly Avenue, Arkon, Ohio, 44306) were filled with 6 cm of Lambert© LM-GPS Professional Growing Media (Lambert Peat Moss, 106 Chem. Lambert, Riviére-Ouelle, Québec, G0L 2C0, Canada), followed by 3 cm of field soil as the top layer. A single row of small burnet and a single row of Siberian wheatgrass were planted 9 cm from the long sides of the trays and 15 cm apart, forming parallel rows down the length of the trays. Each row contained 18 seeds with 3 cm spacing.

For treatments utilizing activated charcoal, Soap Expressions© Activated Charcoal (Soap Expressions, 3765 Old Easton Rd, Doyletown, PA, 18901) was applied using an airbrush (15 PSI) to the seeding rows in a 3 cm band using a cardboard stencil. Bands of the high rate contained 414 kg ha^{-1} (0.52 oz) of charcoal mixed with 9 ml water, while the lower rate used in the run 2 was 207 kg ha^{-1} (0.26 oz) of charcoal mixed with 9 ml water. The soil surface was lightly misted with water beforehand to prevent soil from being dislocated by the airbrush.

Herbicide broadcast applications consisted of Indaziflam at 44 g ai ha^{-1}, applied in an enclosed laboratory spray chamber (Control Assemblies Co, 15400 Medina Rd, Minneapolis, MN, 55447) (Serial No. SB8-113) on January 6th, 2023, for the first run and on May 3rd, 2023, for the second run. When desired, herbicide exclusion zones (HEZs) were achieved by laying strips of corrugated cardboard over the seed rows during the herbicide application.

The first watering was done using the rainfall simulator feature of the spray chamber 24 hours after treatment, using an TEEJET© 8002VS nozzle for 15 minutes to 5 trays at a time. Once moved to the greenhouse. trays were subsequently watered by misting by hand, twice daily. This was done to minimize soil movement caused by the application of water.

The first trial consisted of 5 replications of 7 treatments (Table 4.2). Each treatment included the broadcast application of indaziflam, then either an HEZ of 2.5 cm, an HEZ of 5 cm, a 2.5 cm preapplication of activated charcoal, or combination thereof. An untreated control and an unprotected treatment were also both included in the study. The treatments of the second trial were similar to the first, but the concentration of the carbon mixture was reduced by half (Table 4.3). An 8th treatment was also added to the second run, which consistent of a 2.5 cm application of the activated charcoal at 414 kg ha^{-1} rate.

Seedlings counts were collected 7 DAT and then every 3-4 days following until 21 DAT. At 21 DAT, plant heights were also collected. Count data was transformed using a simple sqrt transformation to meet the assumptions of normality (Equation 4.3).

$$T_i = \sqrt{(d_i)} \quad \textbf{[4.3]}$$

T_i = transformed data at the ith data point, d_i = ith data point

Above ground biomass was harvested and allowed to dry at room temperature for 2 weeks before being measured. This study was analyzed using a one-way analysis of variance (ANOVA) ($\alpha = 0.05$) for significance and a Fisher's LSD post-hoc test of mean separation.

For all studies, data was processed using R software 'base' (R Core Team 2022), with packages 'agricolae' (de Mendiburu 2021) for ANOVAs, and 'tidyverse' (Wickham *et al.* 2019) for general data organization and manipulation.

Study Results

Field Study

The results of seeding in Falls 2021 and 2022 were evaluated in early Summers 2022 and 2023. In both years significant seedling emergence was observed in the early spring; however, seedlings did not survive the severe drought conditions of Summer 2022 or the heavy field bindweed pressure and grasshopper feeding during Summer 2023. Plant establishment by species is discussed below.

Intermediate wheatgrass. Intermediate wheatgrass was one of two species that had significant differences in seedling density between treatments at 6 MAT (Table 4.4). The only treatment with germination counts significantly higher than the control was a combination application of glyphosate and aminopyralid in Spring 2021 followed by glyphosate in Fall 2021. This treatment had 30x more germination than the untreated planting, and 5x more germination than the next highest treatment. All other treatments were not significantly different from the control. At 18 MAT, seedling density did not significantly differ between treatments, though all treatments trended towards higher counts than the untreated control.

Thickspike wheatgrass. For the thickspike wheatgrass, seedling density was not impacted by treatment at either 6 or 18 MAT(Table 4.4).

Siberian wheatgrass. For Siberian wheatgrass seedling density, significance in the mean separation was only detected at 6 MAT (Table 4.5). Of the 12 treatments, only the treatment consisting of a single fall application of imazapic and the treatment of glyphosate and aminopyralid followed by glyphosate produced significantly higher germination counts than the untreated control. Several treatments were statistically similar to this mean group and the untreated control.

Small burnet. For the small burnet plantings, no treatment differences were observed at both 6 and 18 MAT (Table 4.5).

Medusahead Control. For visual estimates of medusahead control, no significant differences were found between the untreated control and all other treatments at 6 MAT (Table 4.6); however, the treatments of the double application of glyphosate, glyphosate followed by imazapic, imazapic followed by glyphosate and aminopyralid, the double application of imazapic, glyphosate and aminopyralid followed by glyphosate, and the indaziflam, glyphosate, and aminopyralid followed by indaziflam all trended towards higher levels of medusahead control. By 18 MAT, all treatments except glyphosate followed by imazapic showed significant increases in medusahead control when compared to the untreated control.

Alfalfa Injury. Visual estimates of alfalfa injury found no significant correlation could be found between herbicide treatments and level of injury (Table 4.6). The treatments containing both glyphosate and aminopyralid trended towards highest levels of alfalfa injury, except for the indaziflam + glyphosate + aminopyralid which trended to be similar to the untreated control.

Greenhouse Study

The results of the January 2023 and May 2023 greenhouse trials were evaluated regularly for 30 days following their respective seeding and treatment applications. While no issues arose in the January 2023 study, successful seedling emergence in the May 2023 study was observed in the first few days of the study before intense summer temperatures within the greenhouse resulted in significant plant death. Plant emergence, control, or injury of the respective species is discussed below.

Siberian wheatgrass. The January 2023 iteration of the study found that Siberian wheatgrass emergence in treatments that included the 2.5 cm band of activated charcoal were not significantly different from the germination rates of the untreated control (Table 4.7). All other treatments were significantly less that the untreated control.

The May 2023 iteration of the study, the ANOVA found no significant difference between the emergence count means of any of the treatments, though a trend similar to the January 2023 iteration could be seen (Table 4.8).

Small burnet. Small burnet emergence counts in the January 2023 iteration followed the same pattern as the Siberian wheatgrass, in that treatments that included the 2.5 cm band of activated charcoal were not significantly different from the germination rates of the untreated control (Table 4.9). All other treatments were significantly less that the untreated control.

The May 2023 iteration of the study saw much less variation in treatment means. At 7 DAT, the only treatment to differ significantly from the untreated control was in the unprotected treatment (Table 4.10). At 11 DAT, no treatments were significantly different from the untreated control. At 14 and 18 DAT, only the treatments that included a preapplication of activated charcoal had seedlings numbers similar to the untreated control. At 21 DAT, the only treatment to significantly differ from the untreated control was the treatment with the 2.5 cm HEZ and no activated charcoal. All other treatments at 21 DAT were not significantly different.

Biomass and Height. Small burnet biomass and height in the January 2023 iteration both followed the same pattern (Table 4.11). Both saw that all treatments that included a preapplication of activated charcoal were not significantly different from the untreated control. All other treatments were significantly lower than the untreated control.

Biomass for the Siberian wheatgrass in the January 2023 iteration saw a similar pattern as the small burnet, in that only the treatments that included a preapplication of activated charcoal were not significantly reduced from the untreated control (Table 4.11), On the contrary, these treatments all saw a significant increase in the wheatgrass biomasses. Siberian wheatgrass height in this iteration of the study was not significantly different between any of the treatments.

In the May 2023 iteration, neither the small burnet height, small burnet biomass, nor the Siberian wheatgrass biomass were significantly different from the untreated controls (Table 4.12). The Siberian wheatgrass height in this iteration of the study found that all treatments that included a preapplication of activated charcoal, as well as the treatment with just the 5 cm HEZ, were not significantly different from the untreated control.

Discussion

Precipitation. In the field study, climate proved to be a strong confounding variable. Climate data collected from the Brigham City Waste Plant Weather Station (about 33 km south, and the closest weather station) report that between July 2021 and June 2022, the regions accumulated 26 cm of precipitation, whereas the same region received 56 cm of precipitation between July 2022 and June 2023 (NOAA 2023). With such climate inputs, germination at 6 MAT was reduced across the board so that few of the treatments were significantly different from the untreated control. Similarly, germination at 18 MAT was greatly impacted by the above average levels of precipitation.

Efficacy of 'multi-entry' approaches. The reseeding data collected from this study was rarely significantly different from the untreated control, due to both years of observations being in their own climate extreme. While these extremes muddied the difference between the treatments, the study was able to demonstrate that germination can occur in indaziflam treated soils. The seedings that germinated were planted 12 months after the application of the herbicides and in a year with significant moisture. This shows that there are conditions in which indaziflam can be integrated into direct seeding based revegetation plans.

Of the 12 treatments, only five saw significantly high levels of medusahead control, with numerically low levels of injury to alfalfa: glyphosate followed by glyphosate, imazapic followed by glyphosate, single application of glyphosate, single application of imazapic, and indaziflam + glyphosate + aminopyralid followed by glyphosate. While the alfalfa injury measurements were not significantly different from each other in this study, there data suggests that usage of indaziflam on alfalfa does not correlate with alfalfa injury, while still contributing to extended control of medusahead.

Efficacy of artificial safe sites. Of the two artificial safe site methods tested, the application of activated charcoal over the seed rows before indaziflam application provided the most consistent results. All treatments including activated charcoal saw improved growth over the length of the study. This is consistent with similar studies; however, it also provides a potentially cheaper method for applying activated charcoal than as a seed coating. Activated charcoal has the potential to be an important tool in revegetating degraded wildlands when using indaziflam, as broadcast applications prior to herbicide applications has the potential to lead to safe sites formation for desirable seed germination, as expressed in Clenet *et al.* 2019.

The failure of the HEZs to promote germination likely was a result of the field soil used in this study. It should be noted that there is a discrepancy between the data collected from the USDA Web Soil Survey and the USU Analytical Laboratories. The former states the soil to be a silty clay, while the latter claims it to be a silt loam. The soil did have a noticeable amount of clay in it, and it is possible that the inefficacy of the HEZs is directly related to the soils high clay content. Clay soil generally has very low water intake, between 0.03 and 0.3 cm per hour (Kopec 1995). Even with the watering precautions taken to avoid flooding, it is unlikely that the hose and mister were able to achieve such a low rate. The buildup of water on the soil surface could have mobilized the fine soil particles, and with them, the otherwise immobile indaziflam chemical.

Further studies will be needed to determine how low of an application of the activated charcoal could be applied and still achieve an acceptable germination rate, as our study only looked at high rates of activated charcoal. Likewise, studies will be needed to better understand the relationship between movement of indaziflam and clay soil to further confirm this hypothesis.

Future studies. The main purpose of these studies was to explore the potential for the integration of indaziflam into direct seeding management plans. To those ends, the field trial did find that it is possible for both the herbicide and the direct seeding approach to occur, given that the herbicide is applied before a dry year, and seeding occurs 12 MAT and right before a wet year. While the ability to make such accurate predictions is difficult, these results do suggest that such a union of these two tools is indeed possible.

The greenhouse parts of this study provided evidence to suggest that the application of activated charcoal just before herbicide application does protect seed rows. In future studies, both charcoal dosage and scale will need to be explored if broadcast applications activated charcoal is going to make its way into the revegetation plan of public and agency land managers. Similarly, herbicide exclusions zones though temporary, physical barriers may still be viable option, potentially in silt and loamy soils, however further experimentation will be needed.

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Data Tables

Table 4.1. Treatments applied to explore multi-entry herbicide application strategies for seeding into a degraded plant community near Riverside, UT. Treatments were applied in May 2021 and followed-up with in November 2021

Spring 2021 Timing		Fall 2021 Timing	
Treatment*	Rate	Treatment*	Rate
	g ai ha^{-1}		g ai ha^{-1}
Untreated			
Glyphosate	210	Glyphosate	210
Glyphosate	210	Glyphosate + Aminopyralid	210 + 102
Glyphosate	210	Imazapic	140
Imazapic	140	Glyphosate	210
Imazapic	140	Glyphosate + Aminopyralid	210 + 102
Imazapic	140	Imazapic	140
Glyphosate	210		
Glyphosate + Aminopyralid	210 + 102		
Imazapic	140	Untreated	
Glyphosate + Aminopyralid	210 + 102	Glyphosate	210
Indaziflam + Glyphosate + Aminopyralid	44 + 210 + 102	Glyphosate	210

*All treatments included a non-ionic surfactant at 0.25% v/v.

Table 4.2. Treatments applied to test germination of two desirable species planted into indaziflam treated soils in a greenhouse environment in January 2022.

Treatment*	Rate	HEZ	Activated charcoal
	g ai ha^{-1}	cm	kg ha^{-1}
Untreated			
Indaziflam	44		
Indaziflam	44	2.5	
Indaziflam	44	5.0	
Indaziflam	44		414
Indaziflam	44	2.5	414
Indaziflam	44	5.0	414

*All treatments contained a non-ionic surfactant at 0.25% v/v.

Table 4.3. Treatments applied to test germination of two desirable species planted into indaziflam treated soils in a greenhouse environment in May 2022.

Treatment*	Rate	HEZ	Activated charcoal
	g ai ha^{-1}	cm	kg ha^{-1}
Untreated			
Indaziflam	44		
Indaziflam	44	2.5	
Indaziflam	44	5.0	
Indaziflam	44		207
Indaziflam	44	2.5	207
Indaziflam	44	5.0	207
Indaziflam	44		414

*All treatments contained a non-ionic surfactant at 0.25% v/v.

Table 4.4. Germination counts for two grass species in response to treatments from a study explore multi-entry herbicide applications when reseeding a degraded landscape near Riverside, UT. Herbicide applications were made in Spring and Fall of 2021. Seeding was completed directly following the Fall 2021 herbicide applications. Data was collected in early summer ever year following the final treatment application.

Spring 2021		Fall 2021		Intermediate wheatgrass		Thickspike wheatgrass	
Treatments*	Rate	Treatments*	Rate	6 MAT[†]	18 MAT[†]	6 MAT[†]	18 MAT[†]
	g ai ha^{-1}		g ai ha^{-1}	plants m^{-2}			
Untreated				1 bc	38	0	65
Glyphosate	210	Glyphosate	210	1 bc	82	0	74
Glyphosate	210	Glypho + amino	210 + 102	1 bc	81	1	37
Glyphosate	210	Imazapic	140	0 c	112	1	63
Imazapic	140	Glyphosate	210	3 bc	113	1	100
Imazapic	140	Glypho + amino	210 + 102	3 b	84	1	69
Imazapic	140	Imazapic	140	1 bc	128	0	95
Glyphosate	210			2 bc	64	0	70
Glyphosate	210	Aminopyralid	102	2 bc	96	1	96
Imazapic	140			1 bc	81	1	80
Glypho + amino	210 + 102	Glyphosate	210	16 a	82	3	77
Indaz + glypho + amino	44 + 210 + 102	Glyphosate	210	1 bc	100	0	46
Treatment p-values				0.04[‡]	0.20	0.14	0.40

[*] All treatments contained a non-ionic surfactant at 0.25% v/v.

[†] Values under this header labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

[‡] P-value less than 0.05.

Table 4.5. Germination counts of one grass species and one forb species in response to treatments from a study explore multi-entry herbicide applications when reseeding a degraded landscape near Riverside, UT. Herbicide applications were made in Spring and Fall of 2021. Seeding was completed directly following the Fall 2021 herbicide applications. Data was collected in early summer ever year following the final treatment application.

Spring 2021		Fall 2021		Siberian wheatgrass		Small burnet	
Treatments*	Rate	Treatments*	Rate	6 MAT[†]	18 MAT[†]	6 MAT[†]	18 MAT[†]
	g ai ha^{-1}		g ai ha^{-1}	plants m^{-2}			
Untreated				0 b	84	1	18
Glyphosate	210	Glyphosate	210	0 b	111	1	30
Glyphosate	210	Glypho + amino	210 + 102	0 b	111	0	25
Glyphosate	210	Imazapic	140	0 ab	128	1	37
Imazapic	140	Glyphosate	210	0 b	139	0	27
Imazapic	140	Glypho + amino	210 + 102	0 ab	102	0	7
Imazapic	140	Imazapic	140	0 ab	125	0	29
Glyphosate	210			1 ab	99	2	39
Glyphosate	210	Aminopyralid	102	0 ab	129	0	17
Imazapic	140			1 a	113	0	14
Glypho + amino	210 + 102	Glyphosate	210	1 a	121	0	24
Indaz + glypho + amino	44 + 210 + 102	Glyphosate	210	0 ab	122	1	30
Treatment p-values				<0.01[‡]	0.33	0.57	0.70

[*] All treatments contained a non-ionic surfactant at 0.25% v/v.

[†] Values under this header labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

[‡] P-value less than 0.05.

Table 4.6. Medusahead control and alfalfa injury in response to treatments from a study explore multi-entry herbicide applications when reseeding a degraded landscape near Riverside, UT. Herbicide applications were made in Spring and Fall of 2021. Seeding was completed directly following the Fall 2021 herbicide applications. Data was collected in early summer ever year following the final treatment application.

Spring 2021		Fall 2021		Medusahead control			Alfalfa injury	
Treatments*	Rate	Treatments*	Rate	6 MAT[†]	18 MAT[†]		6 MAT[†]	18 MAT[†]
	g ai ha^{-1}		g ai ha^{-1}	——	——	—— %	——	——
Untreated				0	0	e	50	1
Glyphosate	210	Glyphosate	210	11	96	abc	38	37
Glyphosate	210	Glypho + amino	210 + 102	8	94	abc	29	100
Glyphosate	210	Imazapic	140	9	35	de	33	1
Imazapic	140	Glyphosate	210	33	100	ab	23	0
Imazapic	140	Glypho + amino	210 + 102	33	100	a	16	100
Imazapic	140	Imazapic	140	35	54	cd	18	15
Glyphosate	210			3	93	abc	38	4
Glyphosate	210	Aminopyralid	102	4	100	ab	38	100
Imazapic	140			1	63	bcd	50	9
Glypho + amino	210 + 102	Glyphosate	210	23	100	a	85	100
Indaz + glypho + amino	44 + 210 + 102	Glyphosate	210	33	99	ab	28	1
Treatment p-values				0.13	<0.01[¶]		0.43	0.94

[*] All treatments contained a non-ionic surfactant at 0.25% v/v.

[†] Values under this header labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

[¶] P-value less than 0.05.

Table 4.7. Small burnet germination counts in response to treatment from a study test the germination of two desirable species planted into indaziflam treated soils in a greenhouse environment in January 2023.

				Small burnet emergence				
Treatment*	Rate	HEZ§	Carbon‡	7 DAT†	11 DAT†	14 DAT†	18 DAT†	21 DAT†
	g ai ha^{-1}	cm	kg ha^{-1}	plants per tray				
Untreated				10 a	12 a	11 a	10 a	10 a
Indaziflam	44			0 c	0 c	0 d	0 c	0 c
Indaziflam	44	2.5		0 c	0 c	0 c	0 c	0 c
Indaziflam	44	5.0		2 b	2 b	2 b	1 b	1 b
Indaziflam	44		414	11 a	11 a	10 a	9 a	9 a
Indaziflam	44	2.5	414	10 a	11 a	10 a	9 a	9 a
Indaziflam	44	5.0	414	10 a	11 a	10 a	11 a	11 a
Treatment p-values				<0.01¶	<0.01¶	<0.01¶	<0.01¶	<0.01¶

*All treatments contained a non-ionic surfactant at 0.25% v/v.

§ Herbicide exclusion zones (HEZs) were created by overly seed rows with 2.5 or 5.0 cm wide stripes of corrugated cardboard.

‡Activated charcoal was applied in a 2.5 cm band directly over the seed row.

† Values under this header labeled with the same letter are not significantly different according to Fisher’s LSD at α = 0.05.

¶ P-value less than 0.05.

Table 4.8. Small burnet germination counts in response to treatment from a study to test the germination of two desirable species planted into indaziflam treated soils in a greenhouse environment in May 2023.

Treatment*	Rate	HEZ[§]	Carbon[‡]	Small burnet emergence				
				7 DAT[†]	11 DAT[†]	14 DAT[†]	18 DAT[†]	21 DAT[†]
	g ai ha^{-1}	cm	kg ha^{-1}	plants per tray				
Untreated				3 ab	2 ab	0 a	0 a	2 a
Indaziflam	44			0 c	0 b	0 b	0 b	0 ab
Indaziflam	44	2.5		0 bc	0 b	0 b	0 b	0 b
Indaziflam	44	5.0		1 abc	1 ab	0 b	0 b	0 ab
Indaziflam	44		207	2 ab	2 ab	0 ab	0 ab	1 ab
Indaziflam	44	2.5	207	3 abc	3 a	1 a	1 a	2 ab
Indaziflam	44	5.0	207	2 a	2 ab	2 a	1 a	2 ab
Indaziflam	44		414	1 abc	1 ab	1 ab	0 ab	1 ab
Treatment p-values				0.04[¶]	0.02[¶]	0.06	0.05	0.03[¶]

[*] All treatments contained a non-ionic surfactant at 0.25% v/v.

[§] Herbicide exclusion zones (HEZs) were created by overly seed rows with 2.5 or 5.0 cm wide stripes of corrugated cardboard.

[‡] Activated charcoal was applied in a 2.5 cm band directly over the seed row.

[†] Values under this header labeled with the same letter are not significantly different according to Fisher’s LSD at α = 0.05.

[¶] P-value less than 0.05.

Table 4.9. Siberian wheatgrass germination counts in response to treatment from a study to test the germination of two desirable species planted into indaziflam treated soils in a greenhouse environment in January 2023.

				Siberian wheatgrass emergence									
Treatment*	Rate	HEZ[§]	Carbon[‡]	7 DAT[†]		11 DAT[†]		14 DAT[†]		18 DAT[†]		21 DAT[†]	
	g ai ha^{-1}	cm	kg ha^{-1}	plants per tray									
Untreated				8	a	9	a	9	a	9	b	9	b
Indaziflam	44			0	b	0	b	0	b	0	c	0	c
Indaziflam	44	2.5		0	b	1	b	0	b	0	c	1	c
Indaziflam	44	5.0		2	b	2	b	1	b	0	c	1	c
Indaziflam	44		414	8	a	11	a	11	a	11	ab	11	ab
Indaziflam	44	2.5	414	14	a	14	a	14	a	14	a	15	a
Indaziflam	44	5.0	414	11	a	12	a	14	a	14	a	14	ab
Treatment p-values				<0.01[¶]		<0.01[¶]		<0.01[¶]		<0.01[¶]		<0.01[¶]	

[*] All treatments contained a non-ionic surfactant at 0.25% v/v.

[§] Herbicide exclusion zones (HEZs) were created by overly seed rows with 2.5 or 5.0 cm wide stripes of corrugated cardboard.

[‡] Activated charcoal was applied in a 2.5 cm band directly over the seed row.

[†] Values under this header labeled with the same letter are not significantly different according to Fisher’s LSD at α = 0.05.

[¶] P-value less than 0.05.

Table 4.10. Siberian wheatgrass germination counts in response to treatment from a study to test the germination of two desirable species planted into indaziflam treated soils in a greenhouse environment in May 2023.

				Siberian wheatgrass emergence				
Treatment*	Rate	HEZ[§]	Carbon[‡]	7 DAT[†]	11 DAT[†]	14 DAT[†]	18 DAT[†]	21 DAT[†]
	g ai ha^{-1}	cm	kg ha^{-1}	——— plants per tray ———				
Untreated				5	6	3	3	6
Indaziflam	44			0	0	0	0	0
Indaziflam	44	2.5		3	2	1	4	2
Indaziflam	44	5.0		5	2	2	1	5
Indaziflam	44		207	2	2	0	1	1
Indaziflam	44	2.5	207	3	7	4	4	5
Indaziflam	44	5.0	207	9	8	7	6	8
Indaziflam	44		414	3	3	1	2	2
Treatment p-values				0.13	0.36	0.14	0.12	0.26

[*] All treatments contained a non-ionic surfactant at 0.25% v/v.

[§] Herbicide exclusion zones (HEZs) were created by overly seed rows with 2.5 or 5.0 cm wide stripes of corrugated cardboard.

[‡] Activated charcoal was applied in a 2.5 cm band directly over the seed row.

[†] Values under this header labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

[¶] P-value less than 0.05.

Table 4.11. Biomass and heights in response to treatment from a study test the germination of two desirable species planted into indaziflam treated soils in a greenhouse environment in January 2023.

				Small burnet				Siberian Wheatgrass		
Treatment*	Rate	HEZ§	Carbon‡	Biomass†		Height†		Biomass†	Height†	
	g ai ha^{-1}	cm	kg ha^{-1}	mg		cm		mg	cm	
Untreated				442	a	3	b	48	7	d
Indaziflam	44			0	b	0	d	0	0	f
Indaziflam	44	2.5		0	b	0	d	0	1	ef
Indaziflam	44	5.0		40	b	1	c	13	2	e
Indaziflam	44		414	601	a	4	ab	93	10	c
Indaziflam	44	2.5	414	678	a	4	a	139	13	b
Indaziflam	44	5.0	414	621	a	3	b	396	15	a
Treatment p-values				<0.01¶		<0.01¶		0.09	<0.01¶	

[*] All treatments contained a non-ionic surfactant at 0.25% v/v.

[§] Herbicide exclusion zones (HEZs) were created by overly seed rows with 2.5 or 5.0 cm wide stripes of corrugated cardboard.

[‡] Activated charcoal was applied in a 2.5 cm band directly over the seed row.

[†] Values under this header labeled with the same letter are not significantly different according to Fisher’s LSD at α = 0.05.

[¶] P-value less than 0.05.

Table 4.12. Biomass and heights in response to treatment from a study to test the germination of two desirable species planted into indaziflam treated soils in a greenhouse environment in May 2023.

				Small burnet		Siberian Wheatgrass	
Treatment*	Rate	HEZ§	Carbon‡	Biomass†	Height†	Biomass†	Height†
	g ai ha^{-1}	cm	kg ha^{-1}	mg	cm	mg	cm
Untreated				12	0	6	3 ab
Indaziflam	44			0	0	1	1 d
Indaziflam	44	2.5		0	0	2	1 cd
Indaziflam	44	5.0		1	0	6	2 abc
Indaziflam	44		207	9	1	1	2 bcd
Indaziflam	44	2.5	207	6	0	5	3 a
Indaziflam	44	5.0	207	1	1	7	3 a
Indaziflam	44		414	19	0	1	3 ab
Treatment p-values				0.71	0.43	0.62	0.03¶

*All treatments contained a non-ionic surfactant at 0.25% v/v.

§ Herbicide exclusion zones (HEZs) were created by overly seed rows with 2.5 or 5.0 cm wide stripes of corrugated cardboard.

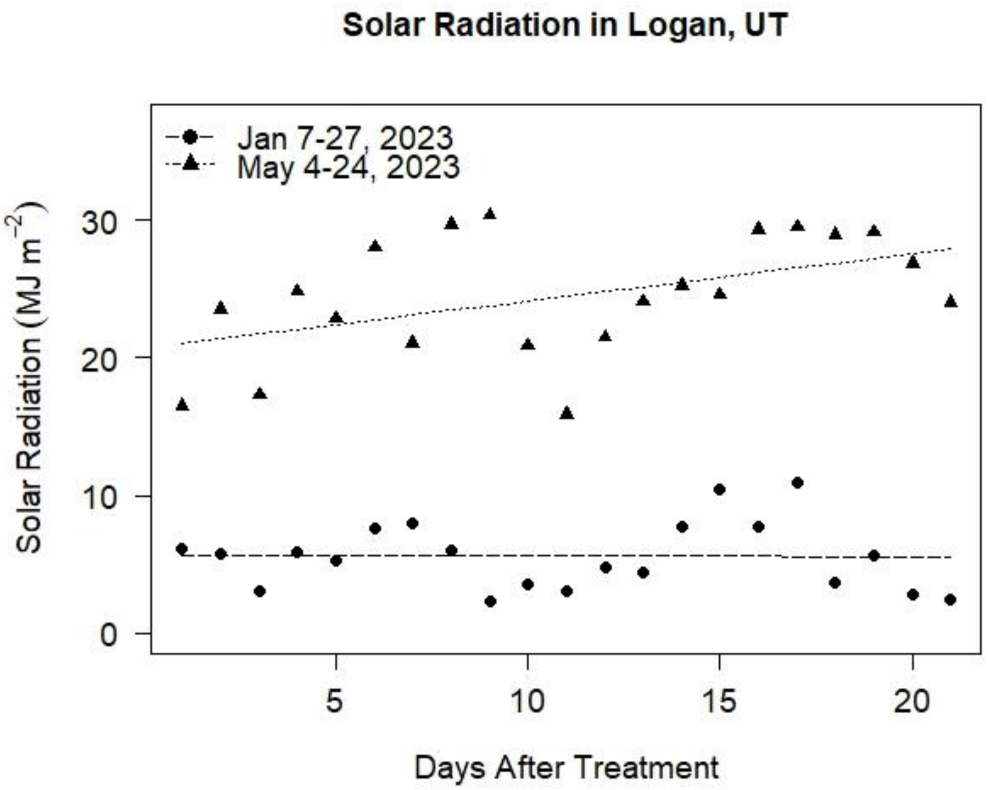
‡Activated charcoal was applied in a 2.5 cm band directly over the seed row.

† Values under this header labeled with the same letter are not significantly different according to Fisher's LSD at α = 0.05.

¶ P-value less than 0.05.

Data Figure

Figure 4.1. Daily accumulated shortwave solar radiation, as collected by USU campus weather station during two studies to test the germination of two desirable species planted into indaziflam treated soils in a greenhouse environment started in January and May 2023.



CHAPTER V

Summary and Conclusions

As of 2005, invasive annual grasses were a large contributor to the estimated $6 billion annual cost for loss and damages caused by invasive plants to wild- and rangeland managers (Pimental *et al.* 2005). Contemporary studies also found over 31.5 million acres of the Great Basin region was covered in these grasses (Menakis *et al.* 2003). There is little doubt that those values, $6 billion and 31.5 million acres, have only grown larger in the last 20 years. These grasses, namely downy brome (*Bromus tectorum*), ventenata (*Ventenata dubia*), and medusahead (*Taeniatherum caput-medusae*), are widely known for their reduced grazing potential, aggressive propagation, and increased fire risks (Lehnhoff *et al.* 2019, Williamson *et al.* 2020).

The recent development of the herbicide indaziflam has provided some hope for controlling future spread of these grasses (Sebastion *et al*. 2017a) Indaziflam is a soil persistent herbicide that inhibits seed germination for 3-5 years (Sebastion *et al.* 2017b). While this is a boon for managing *Bromus tectorum* seeds, which can survive in the soil for 1 to 3 years (Seipel n.d.), this has also brought about concern for long-term ecological impacts that would not appear in the 2–3-year scope of many studies. This thesis seeks to address these concerns by analyzing the effects of indaziflam applications at two sites of varying levels of invasive annual grass infestation of a 5-year period.

A site near Richmond, UT, was selected for its high biodiversity and a mild downy brome infestation. A study consisting of multiple herbicide treatments, including low rates of indaziflam, were established in 2017 and then replicated again in an adjacent site in 2018 to allow for long term monitoring of the ecological effects of indaziflam applications on a considerably healthy landscape. The effects monitored were percent cover (individual species, desirables, and invasives), richness (total, desirables, and invasives), diversity (Shannon Diversity Index), and evenness (Pielou Evenness Index). The first run of the study found that plots treated with indaziflam often showed decreased levels of invasive plant cover and richness, while metrics like diversity, evenness, and desirable plant cover were not negatively impacted. The second run found similar results: invasive plant cover and richness drastically reduced, with desirable plant cover unaffected. Diversity and evenness were negatively affected in the second run; however, further analysis revealed the reductions were similar to a loss of 1-2 equally frequency species.

A site near Mt. Sterling, UT, was selected for the reasons opposite the Richmond site. This site had poor biodiversity with an intense infestation of ventenata. Treatments similar to those applied at the Richmond site were applied, including quinclorac in 2017 study and a low rate of indaziflam in the 2018 study. The same metrics were measures at this site as at the site near Richmond, UT. During the first run, dramatic decrease in invasive species cover were recorded in the plots treated with indaziflam, while the desirable plant cover was not affected. Invasive richness was not affected by the treatments, and desirable richness was practically equal across all the plots by the 5th year. Biodiversity and evenness also saw that same trend, being practically equal to the untreated control by the 5th year. The second run, indaziflam-treated plot saw decreases in invasive plant cover and richness and increases desirable plant cover and richness. There was no evidence that diversity or evenness were negatively impacted by indaziflam.

In both sites, when indaziflam-inclusive mixtures did result in a negative impact to a metric, it was very often correlated with the impacts caused by the other added herbicide.

Both the Richmond and Mt. Sterling data were compared to precipitation trends recorded at local weather stations. At both sites, the extreme drought conditions recorded in the 2020-2021 growing year correlated with decreases in cover, diversity, richness, etc. in that same growing year. However, this pattern was much more prevalent at the Mt. Sterling site due to the degraded nature of the landscape and the increased presence of invasive annual plants.

Several smaller scale studies were also performed to explore different avenues of approach for revegetating indaziflam-treated areas, including multiple-entry, physical herbicide exclusion, and herbicide tolerance examination.

A site near Riverside, UT was selected for a “multiple-entry” revegetation study. This site was heavily infested with medusahead, with scattered alfalfa (*Medicago sativa*) and sagebrush (*Artemisia tridentata*). Multiple herbicide combinations, with different application timings, were applied. Several different revegetation species were also planted in perpendicular rows to the herbicide treatments in each of the repetitions. The study found that, when reseeded 12 months after the indaziflam application, following a season of heavy precipitation, seedling density in the treated plots were not significantly different from the untreated control plots, or that of any other of the herbicide combinations tested.

A greenhouse study was implemented to test the efficacy of physical and chemical barriers at creating safe-sites in indaziflam treated areas. This study consisted of seed rows being planted in field soil and sprayed with a low rate of indaziflam. In some of the treatments, a physical barrier was laid over the top of the seed row at the time of the herbicide application. In others, a layer of activated charcoal was sprayed over the seed row was sprayed on before the herbicide application. Some treatments contained both forms of protection. In the first run, there was a district, significant separation between the treatments that contained activated charcoal, and those that did not. Treatments with the activated charcoal saw germination counts similar to that of the untreated control, while those without had very low seedling emergence of the 21 days of the study. In the second run, a similar trend was noted early in the study; however, unfavorably high temperatures resulted in large rates of germination failure. By the end of the second run, no difference was noted in any of the treatments in either planted species.

This research sought to achieve two goals. The first was to provide a response to the concerns of potential long-term ecological impacts that might arise from indaziflam applications. This was achieved by showing that, over a length of five years, there were no differences in the ecological metrics, besides that of removing the targeted species. The second was to explore new ways in which revegetation might occur on indaziflam-treated landscape. This was achieved as the field study near Riverside, UT, was able to demonstrate that, given favorable conditions, germination densities in indaziflam treated plots can be statistically similar to those of the untreated control plots. Moreover, the greenhouse study showed that there is evidence that a preapplication of broadcast activated charcoal will enable seedling germination in soil recently treated with indaziflam.

Indaziflam can be a powerful tool in the hands of land managers across the Western US. This thesis adds to a growing body of literature that claim that indaziflam is safe, effective, and has the potential to revolutionize how invasive annual grasses can be managed; however, there is still much to be learned.

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