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Control of Three Invasive Annual Grasses in Utah Using Herbicides Including Indaziflam

Hailey L. Buell
Utah State University

CONTROL OF THREE INVASIVE ANNUAL GRASSES IN UTAH USING

HERBICIDES INCLUDING INDAZIFLAM

by

Hailey L. Buell

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Approved:

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

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ABSTRACT

Control of Three Invasive Annual Grasses in Utah Using Herbicides Including Indaziflam

by

Hailey L. Buell, Master of Science

Utah State University, 2021

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

Three invasive annual grasses: downy brome, ventenata, and medusahead have become a concern on rangelands in northern Utah. Field and greenhouse studies were established to test the efficacy of indaziflam, a relatively new preemergence herbicide, and other herbicides alone and in combination.

A study was established on a site near Richmond, Utah that has an existing stand of desirable vegetation as well as downy brome to evaluate the tolerance of all species present to indaziflam alone and in combination. All treatments including indaziflam reduced downy brome cover in both runs up to 20 months after treatment. Total species richness was reduced with indaziflam treatments, but native richness was maintained or increased with most treatments including those with indaziflam.

A field study was established near Mt. Sterling, Utah, one of the only sites where ventenata is present in Utah. The study was designed to test the efficacy of indaziflam and other herbicides on ventenata as well as evaluating response of the surrounding vegetation. Treatments most effective for controlling ventenata included indaziflam or rimsulfuron, whereas glyphosate and imazapic alone were among the least effective. Species richness generally increased with indaziflam treatments. Aminopyralid nearly doubled ventenata cover and severely reduced cover of broadleaf plants.

A greenhouse study was established alongside the field study to test three herbicides: rimsulfuron, imazapic, and glyphosate at increasing rates on ventenata, medusahead, and downy brome in a controlled environment. Overall, the three grasses were more sensitive to rimsulfuron than the other herbicides. Glyphosate was the least effective of all the treatments; however, ventenata was much more sensitive to glyphosate in the greenhouse than it is typically observed to be in the field.

A site near Honeyville, Utah was chosen for a multiple-entry revegetation study due to the near monoculture of medusahead present. It was designed as a strip-plot study with comparable treatments applied to each strip. One strip was seeded immediately following application while the other was seeded one year after. Treatments were altered after the first planting failed. Re-seeded species generally established better in the multiple-entry plots except those treated with indaziflam. Amount of precipitation was positively correlated with establishment.

(112 pages)

PUBLIC ABSTRACT

Control of Three Invasive Annual Grasses in Utah Using Herbicides Including Indaziflam

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Invasive grasses pose a threat to rangeland ecosystems in Utah. Three grasses in particular: downy brome, medusahead, and ventenata can push out native plants and prevent other vegetation from germinating. These grasses can also degrade grazing lands for cattle and act as kindling for wildfires. The use of herbicides is the most common way to rid a site of invasive plants. Herbicides that prevent germination for many years work well to keep annual grasses at bay while not harming the many long-living native plants that are already growing.

A study was designed on a site infested with downy brome to test how well native plants tolerate a variety of herbicides. The main objective was to test for lone herbicides or combinations that do minimal damage to the native vegetation with maximum damage to downy brome.

Ventenata is an invasive grass that is new to Utah; thus, not much is known about how to control it. An experiment was designed to test different herbicides on a site invaded by ventenata and observe the effects on the surrounding native and weedy plants. A concurrent greenhouse study was designed to test three different herbicides on downy brome, ventenata, and medusahead to see how they react differently in controlled conditions compared to field conditions.

An experiment was designed to restore a site that had been completely overtaken by medusahead using herbicides. The site was sprayed with a variety of different herbicides. Native and other desirable plants were planted using a drill into the site in order to see which herbicides prevented medusahead germination while allowing maximum establishment of the plants that were seeded.

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CONTENTS

Page

ABSTRACT iii

PUBLIC ABSTRACT v

ACKNOWLEDGMENTS vii

LIST OF TABLES x

LIST OF FIGURES xii

CHAPTER

I. LITERATURE REVIEW 1

Classification and History 1
Morphology 3
Biology 5
Distribution and Ecology 7
Control 10
Research Objectives 12
Literature Cited 13

II. IMPACTS OF HERBICIDES ON DESIRABLE VEGETATION AND DOWNY BROME IN NORTHERN UTAH 20

Abstract 20
Introduction 21
Materials and Methods 23
Results 24
Discussion 36
Literature Cited 38

III. VENTENATA CONTROL AND PLANT COMMUNITY RESPONSE TO HERBICIDE TREATMENTS 40

Abstract 40
Introduction 41
Materials and Methods 43
Results 45
Discussion 66
Literature Cited 72

IV. RESTORATION OF ONE MEDUSAHEAD INFESTED SITE IN UTAH USING A MULTIPLE-ENTRY APPROACH 76

Abstract 76
Introduction 77
Materials and Methods 79
Results 84
Discussion 90
Literature Cited 93

V. SUMMARY AND CONCLUSIONS 97

Literature Cited 100

LIST OF TABLES

Table Page

2.1 Downy brome and other dominant species cover in response to herbicide treatments over time. Run 1 established in 2017. 25

2.2 Downy brome and other dominant species cover in response to herbicide treatments over time. Run 2 established in 2018. 26

2.3 Percent cover of weeds and natives in response to herbicide treatments over time. Run 1 established in 2017. 28

2.4 Percent cover of weeds and natives in response to herbicide treatments over time. Run 2 established in 2018. 29

2.5 Total plant community species richness; weed richness and native richness in response to herbicide treatments. Run 1 established in 2017. 31

2.6 Total plant community species richness; weed richness and native richness in response to herbicide treatments. Run 2 established in 2018. 32

2.7 Diversity scores and evenness in response to herbicide treatments over time. Run 1 established in 2017. 34

2.8 Diversity scores and evenness in response to herbicide treatments over time. Run 2 established in 2018. 35

3.1 Ventenata and other dominant grass cover in response to herbicide treatments over time. Run 1 established in 2017. 47

3.2 Prickly lettuce and wild onion cover in response to herbicide treatments over time. Run 1 established in 2017. 48

3.3 Ventenata and other grass cover in response to herbicide treatments over time. Run 2 established in 2018. 49

3.4 Prickly lettuce, wild onion, and western aster cover in response to herbicide treatments over time. Run 2 established in 2018. 50

3.5 Plant community species richness response to herbicide treatments over time. Run 1 established in 2017. 51

3.6 Plant community species richness response to herbicide treatments over time. Run 2 established in 2018. 52

3.7 Diversity scores and evenness in response to herbicide treatments over time. Run 1 established in 2017. 54

3.8 Diversity scores and evenness in response to herbicide treatments over time. Run 2 established in 2018. 55

3.9 Parameter estimates for 3-parameter dose-response curves describing herbicide by species (Equation 1). 64

3.10 Parameter estimates for 3-parameter dose-response curves describing species in response to herbicide (Equation 1) with EC 50 values expressed as proportions of maximum field rates. 65

4.1 Re-seeded grass species densities in response to herbicide treatments over time. Run 1 established in 2017. 86

4.2 Re-seeded broadleaf species densities in response to herbicide treatments over time. Run 1 established in 2017. 87

4.3 Re-seeded grass species densities in response to herbicide treatments over time. Run 2 established in 2018. 88

4.4 Re-seeded broadleaf species densities in response to herbicide treatments over time. Run 2 established in 2018. 89

LIST OF FIGURES

Figure Page

3.1 Average and cumulative precipitation near Mt. Sterling, Utah. 57

3.2 Response of three annual grasses to increasing glyphosate dosage in greenhouse trials. Runs 1 and 2 are illustrated separately. 58

3.3 Response of three annual grasses to increasing imazapic dosage in greenhouse trials. Runs 1 and 2 are illustrated separately. 59

3.4 Response of three annual grasses to increasing rimsulfuron dosage in greenhouse trials. Runs 1 and 2 are illustrated separately. 60

3.5 Regression of downy brome biomass in response to doses of three herbicides represented as a proportion of the maximum labelled rate in a rangeland setting. Runs 1 and 2 are illustrated separately. 61

3.6 Regression of medusahead biomass in response to doses of three herbicides represented as a proportion of the maximum labelled rate in a rangeland setting. Runs 1 and 2 are illustrated separately. 62

3.7 Regression of ventenata biomass in response to doses of three herbicides represented as a proportion of the maximum labelled rate in a rangeland setting. Runs 1 and 2 are illustrated separately. 68

4.1 Plot and treatment map of run 1 Established in 2017 81

4.2 plot and treatment map of run 2 Established in 2018...82

4.3 Average and cumulative precipitation during reseeding trials..........................91

CHAPTER I

LITERATURE REVIEW

Classification and History

Medusahead. The first North American specimen of medusahead (*Taeniatherum caput-medusae* (L.) Nevski.) was collected by Thomas Jefferson Howell in 1887 near Roseburg, Oregon under the name *Elymus caput-medusae* L. (Howell 1903; Young 1992). Since its initial collection, there has been much disagreement among scientists about how to classify this unique plant. Although originally classified as *Elymus* (Frederiksen 1986), morphologists and cytogeneticists generally agree that medusahead does not belong in this genus (Young 1992). Some have argued that it belongs in the genus *Hordeum* (Kellogg 1989; Young 1992) while others have classified it as *Hordelymus* (Frederiksen 1986; Young 1992). In 1934, Russian botanist Sergei Arsenjevic Nevski published the name *Taeniatherum* (Nevski 1934), believing it to be a new genus entirely. This new name is derived from the Greek 'taenia,' meaning ribbon, and 'ather,' meaning awn (Komarov 1963). Prior to 1986, there were three recognized species in *Taeniatherum*: *T. asperum*, *T. caput-medusae*, and *T. crinitum.* In 1986, however; Signe Frederiksen published research suggesting these species were actually subspecies of *T. caput-medusae* (Frederiksen 1986). In his paper, Frederiksen (1986) recognized *T. caput medusae* ssp. *asperum* (Simk.) Melderis, as the subspecies found in North America. Although initially collected in Oregon, specimens were collected in Washington and California soon after. In 1944, medusahead was first documented in Idaho and spread throughout much of the state in the following 15 years (Young 1992).

Downy Brome. Downy brome, *Bromus tectorum* L., was named by Linnaeus in 1753. Since then, there have been no nomenclatural changes to the species (Upadhyaya *et al*. 1986), although Russian literature also recognizes the name *Anisantha tectorum* (L.) Nevski (Kostivkovsky and Young 2000). Other common names include: cheatgrass, downy chess, junegrass, and broncograss (Hickman 1993). The genus name *Bromus* was derived from the ancient Greek words *bromos*, meaning oats, and *broma*, meaning food (Upadhyaya *et al*. 1986; Mitich 1999). The species name *tectorum* originates from the Latin *tector*, meaning thatch, and *tectum*, meaning roof (Morrow and Stahlman 1984; Mitich 1999). It has been suggested that the species evolved in southwestern Asia near the location where cattle, goats, and sheep were initially domesticated (Young *et al.* 1987). Downy brome is native to Eurasia and was introduced to the United States during the mid-nineteenth century before 1861 (Klemmedson and Smith 1964; Mitich 1999). It is possible that the grass was introduced independently several times; it was even deliberately introduced at least once in 1898 at a college experimental farm in Washington (Upadhyaya *et al.* 1986; Young *et al.* 1987). By the early 1900s, it had become widespread throughout the United States (Klemmedson and Smith 1964).

Ventenata. *Ventenata dubia* (Leers) Coss. is a grass in the *Aveneae* tribe that has been present in the Intermountain Northwest since at least the 1950s, but has only become significantly problematic in the past decade (Wallace *et al.* 2015; Wallace and Prather 2016). Previously classified as both *Avena dubia* Leers and *Avena tenuis* Moench, it was combined and reclassified as *Ventenata dubia* (Leers) Coss. with the publication of the new name in 1855 (Tsvelev 1976; Alomran *et al.* 2019; Missouri Botanical Garden

2019). This grass is commonly referred to by its genus name only (ventenata) with other common names including North Africa grass, wiregrass, hairgrass, and softbearded oat grass (DiTomaso and Healy 2007; Wallace *et al.* 2015; Fryer 2017). Although the plant is referred to as North Africa grass, much of its native range is in Europe; the plant is relatively rare in northern Africa (Alomran *et al.* 2019). The first report of ventenata in North America was in 1952 in Washington and was reported to have moved into northern Idaho by 1957 (Old and Callihan 1987; Fryer 2017; Jones *et al.* 2018). It is well established in the Inland Northwest of the United States and has expanded into sagebrush steppe communities in the Pacific Northwest (Jones *et al.* 2018). Not much is known presently about its distribution, abundance, and habitat niche in this area (Jones *et al.* 2018; Davies and Hamerlynck 2019).

Morphology

Medusahead. *T. caput –medusae* is an annual grass in the wheat tribe: *Triticeae.* Its culms are slender, glabrous, and typically range from 10-60 cm in height (Hickman 1993; Barkworth *et al.* 2007). They are generally erect and arise from a decumbent base (Cronquist *et al.* 1977). Leaf blades are narrowly linear, puberulent, and often involute (Komarov 1963; Cronquist *et al.* 1977), possessing nearly inconspicuous auricles (Cronquist *et al.* 1977). Ligules are membranous (Hickman 1993) and generally less than 0.5 mm long. The inflorescence is a spike, 2-4 cm long excluding the awns of the lemmas (Komarov 1963). Each node has two spikelets and each spikelet contains two florets- one fertile and the other reduced or obsolete (Cronquist *et al.* 1997, Hickman 1993). Its characteristic long, twisted awns can be anywhere from 3 cm to 11 cm long (Barkworth *et al.* 2007). After the seeds shatter, the spike remains intact due to a continuous rachis (Monaco *et al.* 2005). Each seed and awn is equipped with minute barbs that promote spread by animals and humans (Young 1992; Monaco *et al.* 2005; Davies and Johnson 2008).

Downy Brome. *B. tectorum* is variable in size with culms ranging from 5-90 cm in length (Barkworth *et al.* 2007). Culms are erect and puberulent below the inflorescence (Komarov 1963; Barkworth 2007). The leaf blades are linear, flat, and without auricles (Hickman 1993). Both the abaxial and adaxial surfaces of the blades are densely pilose (Komarov 1963; Cronquist *et al.* 1977; Barkworth *et al.* 2007). Ligules are glabrous, lacerate-erose, and 1 mm to 3 mm in length (Komarov 1963; Barkworth *et al.* 2007). The inflorescence is a nodding or drooping, densely branched open panicle, and is usually one-sided (Cronquist *et al.* 1977; Hickman 1993; Barkworth *et al.* 2007). Its spikelets are typically 10-20 mm in length and are tinged purple, with each containing 4-8 florets (Barkworth *et al.* 2007). The glumes and lemmas of each floret are veined and the awns are 8-18 mm (Cronquist *et al.* 1977; Hickman 1993; Barkworth *et al.* 2007).

Ventenata. *V. dubia* is an annual grass that is taxonomically similar to grasses in the genera *Avena* and *Trisetum* and is often mistaken as one of these plants or confused with downy brome (Chambers 1984). The culms grow erect from 10 cm to 75 cm and are puberulent below the glabrous nodes (Barkworth *et al.* 2007). As plants mature, nodes darken in color to a distinct purplish-black, contrasting the light green or tan internodes (Fryer 2017). Ligules are hyaline, generally lacerate, and noticeably long, reaching up to

8 mm in length (Hitchcock and Cronquist 1973: Barkworth *et al.* 2007). Leaf blades are flat to involute (Hitchcock and Cronquist 1973). The inflorescence is an open, pyramidal panicle from 15 to 20 cm with 2 to 5 branches present on the lower nodes (Barkworth *et al.* 2007). Spikelets have 2 to 3 florets; the two upper florets are fertile with a conspicuous geniculate awn on the dorsal face (Chambers 1984). The lowest floret is staminate with its lemma bearing a straight awn (Chambers 1984). Rachillas are typically glabrous or abaxially pubescent on occasion with internodes from 1 to 2 mm (Barkworth *et al.* 2007). *V. dubia's* most distinctive identifying features are its seven-nerved glumes and obconical pedicels (Chambers 1984).

Biology

Medusahead. Medusahead is a winter annual grass (Hironaka 1961) that has a great competitive ability especially in the Great Basin region of the western United States (Monaco *et al.* 2005). Much of its ability to displace other species comes from its high silica content (Young 1992). Swenson and colleagues found that medusahead biomass can be from 9% to 14% silica (1964). Medusahead is primarily self-pollinated and can produce enormous amounts of seed, even at a population density of one plant per square foot (Young 1992). Its seeds germinate typically in the fall from October to November but, with enough moisture, germination can continue through winter and spring (Young 1992; Nafus and Davies 2014). Fresh medusahead seed is not germinable, requiring at least 90 days of cold stratification following maturation (Young 1992). After germination, seedling leaves can grow to several inches before growth is interrupted by frigid winter temperatures (Young 1992; Nafus and Davies 2014). Root development can continue throughout the winter and when weather warms, typically in spring, above-ground growth resumes (Hironaka 1961; Nafus and Davies 2014). Strangely, although it is a highly competitive plant, medusahead matures 2-4 weeks after most other annual grasses (Young *et al.* 1970; Young 1992).

Downy Brome. Downy brome is a winter or spring annual of the tribe *Bromeae* ranging from 5-60 cm in height at maturity (Upadhyaya *et al.* 1986). It has a fine, fibrous root system, reproduces predominantly by seed and is mainly self-pollinated (Klemmedson and Smith 1964; Upadhyaya *et al.* 1986; Mitich 1999). Downy brome is a prolific seed producer. According to Young *et al.* (1987), a mature plant with no neighbors can produce up to 5,000 seeds, although plants in dense stands (1000 plants per ft^2) produce 25 seeds on average. Even plants as small as 2.5 cm under severe moisture stress will still produce seed (Morrow and Stahlman 1984). Germination typically occurs in fall and seedlings spend the winter in a semidormant state, resuming aboveground growth the following spring (Mitich 1999). Soon after germination, the fibrous roots grow quickly and crowd out those species that develop later or more slowly (Stewart and Hull 1949). Growth in the spring is rapid and lush and plants typically mature from early to late June (Klemmedson and Smith 1964). The plant requires a period of vernalization to achieve standard flowering; plants germinated in spring produce a small number of panicles and plants germinated in late March or after produce none (Klemmedson and Smith 1964).

Ventenata. *V. dubia* is a winter annual grass with a shallow root system and a relatively high silica content of up to about 9%, reducing the forage quality of the lands it infests

(Wallace *et al.* 2015; Mangold *et al.* 2019; S. Clark, personal communication, March 5, 2020). Its seeds germinate in the fall with warmer temperatures and after fall rains have increased soil moisture (Wallace *et al.* 2015). Ventenata has a short period of seedbank viability with less than 1% of the seed remaining germinable at three years (Wallace *et al.* 2015). Germination requires a period of warm stratification (10-28° C); if exposed to even five days at 5° C, germination can be reduced by nearly three times the typical rate, and seedlings can take over three times as long to emerge (Wallace *et al.* 2015; Fryer 2017). Ventenata generally grows in areas with moderate to high levels of precipitation or in soils that retain moisture, but may spread to drier areas once established (Fryer 2017; Jones *et al.* 2019). A period of vernalization is required for flowering, which occurs in spring around 2 to 4 weeks later than downy brome (Pavek *et al.* 2011). Each individual plant produces 15 to 35 seeds starting in May and can continue until as late as August (Pavek *et al.* 2011; Fryer 2017).

Distribution and Ecology

Medusahead. Medusahead currently infests California, Connecticut, Idaho, Montana, Nevada, New York, Oregon, Pennsylvania, Utah, and Washington (Young 1992; United States Department of Agriculture – Natural Resources Conservation Service). It is native to the Mediterranean region of Eurasia spanning from Portugal and Morocco to Kyrgyzstan (Frederiksen 1986; Barkworth *et al.* 2007). It typically grows in stony soils and it readily invades dry slopes, disturbed rangelands, fallow farmland, and roadsides (Komarov 1963; Barkworth *et al.* 2007). Medusahead grows well on clay textured soils, although it has infested courser soils depending on moisture, and it prefers areas that receive 25 cm to 100 cm of precipitation annually (Young 1992; Nafus and Davies 2014). In its native range, medusahead typically occurs on low plateaus and mountains growing in gravelly, stony soils high in nitrogen (Kostivkovsky and Young 2000). Medusahead litter is slow to decompose, allowing it to build up over time and suppress native vegetation (Davies and Johnson 2008). This buildup of medusahead thatch is a source of fuel for fires, increasing the frequency of wildfires across its range of infestation (Young 1992; Davies and Johnson 2008).

Downy Brome. Downy brome is native to the Mediterranean region of Eurasia and arrived in the United States around the middle of the 19^{th} century (Morrow and Stahlman 1984). It can presently be found in every state to some degree (Stewart and Hull 1949; Upadhyaya *et al.* 1986; United States Department of Agriculture – Natural Resources Conservation Service). It has been introduced to northern Europe, all Canadian provinces, Japan, South Africa, Australia, New Zealand, Iceland, and Greenland (Upadhyaya *et al.* 1986; Mitich 1999). Downy brome is not very stringent in its habitat requirements but typically grows in areas with annual precipitation levels between 15 and 56 cm and at elevations of up to 2700 m (Morrow and Stahlman 1984; Upadhyaya *et al.* 1986). It grows on a variety of soil types and is quick to invade disturbed rangelands and abandoned farmlands (Klemmedson and Smith 1964; Upadhyaya *et al.* 1986). Although the plant is resilient on many types of soil, it does not tolerate well those with high salinity and high pH (Klemmedson and Smith 1964). It does not grow in areas of extreme moisture or extreme aridity and thrives under full sunlight (Klemmedson and Smith 1964;

Mitich 1999). Even though it is a serious invasive weed, it also takes on the role of an important spring forage plant, providing up to 95% of the vegetation on grazing lands in parts of Idaho (Morrow and Stahlman 1984; Mitich 1999).

Ventenata. Much of ventenata's native range is in Europe, spanning from Spain to the Caspian Sea and from Norway to Finland (Alomran *et al.* 2019). It has also been reported at two locations in Japan (Fryer 2017; Alomran *et al.* 2019). Even though it is aggressively invasive in North America, it is listed as endangered or extirpated in some areas of Europe (Fryer 2017; Alomran *et al.* 2019). Ventenata currently infests the Inland North and the Pacific Northwest regions of North America and has been reported in Maine, Wisconsin, Washington, Idaho, Oregon, Montana, Utah, and Wyoming (Barkworth *et al.* 2007; Jones *et al.* 2018; Koby *et al.* 2019). In the United States, it grows at a wide range of elevations, from 10 m to 1800 m and in locations that receive 35 cm to 112 cm of precipitation annually (Pavek *et al.* 2011). Ventenata is found predominantly on south-facing slopes and in clay loam to rocky clay soils with low potassium and phosphorus levels, but it can be present on other aspects and soils in highly disturbed areas (Pavek *et al.* 2011; Fryer 2017; Jones *et al.* 2018).

Control

Invasive annual grasses are a serious issue on rangelands in the Great Basin region of the United States (Monaco *et al.* 2005; Clark *et al.* 2019a). Three of these grasses in particular, downy brome, medusahead, and ventenata, pose a significant threat to biodiversity, soil health, and wildlife habitat (Monaco *et al.* 2005; Wallace and Prather

2016; Davies and Hamerlynck 2019). Medusahead and ventenata are generally unpalatable to livestock and wildlife due to their high silica contents (Young 1992; Wallace *et al.* 2015); downy brome is a valuable forage at the beginning of its life cycle, at maturity, its heavily barbed seeds render it unpalatable as well (Klemmedson and Smith 1964; Upadhyaya *et al.* 1985). These grasses also form dense monocultures that produce thick layers of thatch which greatly impede growth and germination of native and naturalized desirable vegetation (Monaco *et al.* 2005; Clark *et al.* 2019b). In addition to this, downy brome, medusahead, and ventenata litter is also capable of adsorbing 50% or more of applied herbicides, protecting the seeds and seedlings underneath (Clark *et al.* 2019b). Herbicides are among the most common methods used for control of invasive annual grasses (Sebastian *et al.* 2016). A few of the most prevalent herbicides include glyphosate, imazapic, and more recently, indaziflam (Kyser *et al.* 2007; Sebastian *et al.* 2017a; Koby *et al.* 2019).

Glyphosate is a non-selective herbicide that affects the shikimic acid pathway in plants and results in the accumulation of shikimate (Amrhein *et al.* 1980; Espeland and Kilian 2015). In rangeland management efforts, it is often used in conjunction with a selective preemergent herbicide, as control with glyphosate alone can be highly variable (Beck *et al.* 1995; Kyser *et al.* 2013; Koby *et al.* 2019). If applied when perennial plants are dormant, glyphosate can control invasive annual weeds fairly well, but not consistently for more than one year (Sebastian *et al.* 2016; Sebastian *et al.* 2017a). This is mostly due to the fact that glyphosate has a very high soil adsorption coefficient (K_{oc}) of

24,000, meaning that once it enters the soil, it is tightly bound and has virtually no residual activity (Deer 2004).

Imazapic is an acetolactase synthase (ALS) inhibitor that can be selective depending on plant species and rate of application (Tu *et al.* 2001; Mangold *et al.* 2013; Sebastian *et al.* 2016). It is currently one of the most recommended herbicides for invasive annual grass management, and it can control weeds both pre- and post-emergence (Tu. *et al.* 2001; Sebastian *et al.* 2017a). Many studies have shown that imazapic can have strong preemergence control of downy brome and medusahead for at least one year after treatment, whereas postemergence applications are not as effective (Kyser *et al.* 2007; Mangold *et al.* 2013; Sebastian *et al.* 2016). However, Wallace and Prather (2016) found that postemergence applications of imazapic is more effective on ventenata than preemergence applications. Like glyphosate, imazapic has limited potential for long-term annual grass management (Sebastian *et al.* 2017a).

Indaziflam is a relatively new cellulose biosynthesis inhibiting (CBI) herbicide, only EPA registered in 2010 (US EPA 2010; Brabham *et al.* 2014). Herbicides affecting cellulose biosynthesis have not previously been used for weed management in rangeland settings, but since its release, indaziflam has consistently shown two to three years or more of invasive annual grass control (Sebastian *et al.* 2017b; Clark *et al.* 2019a). It has a long half-life of about 150 days and works at much lower doses than imazapic (González-Delgado *et al.* 2015; Sebastian *et al.* 2016). Indaziflam is unique in its ability to strongly suppress both monocots and eudicots; other CBI herbicides only show strong activity on eudicots (Brabham *et al.* 2014). Recent studies that have used indaziflam to manage invasive annual grasses report long-term control with little to no injury to existing perennial grasses and other desirable vegetation (Sebastian *et al.* 2017a; Clark *et al.* 2019a; Koby *et al.* 2019).

Research Objectives

This research was conducted at three sites in northern Utah, each site primarily infested by one of three invasive annual grasses: downy brome, medusahead, and ventenata. Various herbicides were used on each site including indaziflam, glyphosate, and imazapic.

A site in Honeyville, Utah is infested with a near monoculture of medusahead. The research objectives for this site are to 1) determine the efficacy of indaziflam alone and in combinations with other herbicides for management of medusahead, 2) establish native or desirable perennial vegetation on the site through seed mixes, and 3) determine the effects of indaziflam alone and in combination on the establishment and growth of seeded species.

A site established near Richmond, Utah is moderately infested with downy brome with an abundance of native and naturalized vegetation also inhabiting the area. The objectives for this site are to 1) determine the efficacy of indaziflam alone and in combination with other herbicides for management of downy brome, and 2) determine the tolerance of non-target plants including perennial native forbs to indaziflam alone and in combination.

A site near Mt. Sterling, Utah is recently infested with ventenata, a relatively new invader in the Intermountain West. Because little is yet known about how ventenata responds to various herbicides, the purpose of this research is to 1) test the reactions of ventenata to different herbicides alone and in combination with indaziflam and 2) observe the efficacy of these herbicides and combinations for control of ventenata two years after initial treatment. A greenhouse study was established to test the efficacy of glyphosate, imazapic, and rimsulfuron on ventenata compared with downy brome and medusahead.

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CHAPTER II

IMPACTS OF HERBICIDES ON DESIRABLE VEGETATION AND DOWNY BROME IN NORTHERN UTAH

Abstract

Downy brome is a highly invasive annual grass native to the Mediterranean that has spread throughout much of the United States. Indaziflam is a relatively new preemergence herbicide that has a long period of soil residual activity and has been shown to prevent germination of annual grasses for at least three years. This project was established to evaluate the efficacy of herbicides alone or in combination with indaziflam, and to determine perennial forb tolerance to various treatments. Other herbicides include propoxycarbazone, rimsulfuron, glyphosate, and imazapic. Two runs of this study were established at a site near Richmond, Utah that has a variety of native and naturalized perennials and is moderately infested with downy brome. Treatments were applied in the fall of 2016 (run 1) and 2017 (run 2) to plots measuring 6 by 18 m arranged in a randomized complete block design, replicated 4 times. Species cover was evaluated using point-line-intercept transects, recording a point every 15 cm. All treatments including indaziflam reduced downy brome cover in both runs at 7 and 20 months after treatment. Total species richness was reduced with indaziflam treatments, but native species richness was maintained or increased with most treatments including those with indaziflam. This project provides understanding on how herbicide treatments and combinations affect plant community dynamics.

Introduction

Downy brome (*Bromus tectorum* L.), an exotic annual grass, has become one of the most invasive weeds in North America to date, and has infested several million hectares of land since its introduction in the mid-nineteenth century (Morrow and Stahlman 1984; Clark *et al.* 2019). Although typically classified as a winter annual, its seeds are capable of germination during any time of year when conditions are favorable, giving it a competitive advantage over many native species and allowing it to thrive in arid climates by depleting soil moisture before most natives break dormancy (Upadhyaya *et al.* 1986; Clark *et al.* 2019). Downy brome is a prolific, cleistogamous seed producer and, under field conditions, its seed can remain viable for 2-5 years (Upadhyaya *et al.* 1986). It has an extraordinary ability to reproduce; even plants 2.5 cm in height and under severe moisture stress will still produce seed (Morrow and Stahlman 1984). It is especially problematic in the Great Basin region of the United States where it grows in dense monocultures and has contributed to a dramatic increase in fire frequency on rangelands (Stewart and Hull 1949; Young *et al.* 1987; Svejcar *et al.* 2017). It is estimated that 22 million hectares are infested with downy brome in the western United States alone with a 14% annual spread rate (Duncan *et al.* 2004; Sebastian *et al.* 2017a).

Herbicides are one of the most prevalent methods for controlling invasive annual grasses on rangelands (Sebastian *et al.* 2016). Indaziflam, a relatively new herbicide released in 1996 (EPA registered in 2010), has since become the main herbicide for control of downy brome in rangeland and natural settings (US EPA 2010; Clark *et al.*

2019). It has a mode of action that has not been used for weed management in non-crop systems previously; therefore, there is limited information on the impacts this herbicide has on native and naturalized desirable vegetation (Clark *et al.* 2019). Indaziflam is a cellulose biosynthesis inhibitor (CBI) that targets proteins in the cellulose synthase complex different from those targeted by formerly introduced CBIs (Brabham *et al.* 2014). Because of this, plants that are resistant to other common CBIs (Isoxabon and Quinoxyphen) are not cross-resistant to indaziflam (Brabham *et al.* 2014). Unlike other CBIs, indaziflam has strong activity in both monocots and eudicots, whereas most others have strong activity only in eudicots and limited to no activity in monocots (Brabham *et al.* 2014; Sebastian *et al.* 2017b).

Two of the most common herbicides recommended for invasive annual grass management are glyphosate and imazapic, but their control is inconsistent and many plants have already developed resistance to them (Sebastian *et al.* 2017b). Indaziflam has a long period of persistence in soils with a half-life of 150 days (González-Delgado *et al.* 2015) and has been shown to provide three years or more of selective control of invasive annual grasses (Sebastian *et al.* 2017b; Clark *et al.* 2019). Herbicides such as indaziflam will be critical for managing downy brome and other invasive annual grasses on rangelands and other non-crop sites in the coming years. Relatively little is known about the effects of indaziflam in combination with other herbicides (Clark *et al.* 2019). The first objective of this study was to evaluate the efficacy of indaziflam alone and in combinations for management of downy brome at low to moderate densities and the second was to determine the tolerance of native and naturalized perennial vegetation to these herbicides and combinations.

Materials and Methods

A site was chosen near Richmond, Utah (41°55’59.18” N, 111°46’03.83” W; 1695 m elevation) that is moderately infested with downy brome. This site was selected for its exceptional level of biodiversity including many desirable forbs and grasses. Two runs of the experiment were established on the site adjacent to one another in 2017 and 2018, respectively. Plots were 6 m by 18 m replicated four times for each run in a randomized complete block design. Treatments consisted of: an untreated control, indaziflam at 102 g ai/ha, propoxycarbazone at 59 g ai/ha, rimsulfuron at 70 g ai/ha, imazapic at 175 g ai/ha, glyphosate at 532 g ai/ha, indaziflam at 102 g ai/ha with propoxycarbazone at 59 g ai/ha, indaziflam at 102 g ai/ha with rimsulfuron at 70 g ai/ha, indaziflam at 102 g ai/ha with imazapic at 175 g ai/ha, and indaziflam at 102 g ai/ha with glyphosate at 532 g ai/ha. Treatments were applied in October of 2017 and 2018 for runs 1 and 2 respectively. All treatments were applied with a CO_2-pressurized backpack sprayer calibrated to deliver 234 L/ha at 40 psi and all treatments included a non-ionic surfactant at 0.25% v/v.

In the spring following treatment, each plot was visually evaluated for percent control of downy brome and percent injury of desirable vegetation. Plots were evaluated during the summer after treatment for percent cover of each species using the point-line intercept method with data points recorded every 15 cm along a transect line (Elzinga *et* *al* 1998). Transect tapes were run lengthwise through one half of each plot. These data were converted to percent cover and transformed using an arcsin(sqrt) transformation. All data were analyzed using general linear model or repeated measure ANOVA. Diversity and evenness were calculated using the Shannon-Weiner diversity equation (Shannon 1948).

Results

In the first run, downy brome cover was reduced from the untreated in every treatment 7 MAT, but only remained reduced with any treatment including indaziflam 20 MAT (Table 2.1). The same trend was observed in the second run 7 MAT; however, at 20 MAT, all herbicides except glyphosate maintained suppression of downy brome cover compared to the untreated control (Table 2.2). In run 1, treatments had no effect on Hooker's balsamroot, mule's ear, and false sunflower cover, which remained similar from the untreated for all treatments 7 MAT; however, 20 MAT, balsamroot cover decreased and increased in two treatments: rimsulfuron and indaziflam + glyphosate, respectively (Table 2.1). In the second run, balsamroot, lomatium, mule's ear, and false sunflower either remained unchanged or increased compared to the untreated at both evaluation times (Table 2.2). Western wheatgrass was the only dominant desirable species with lower cover compared to the untreated at either evaluation time in both runs. Likewise, prickly lettuce was the only weedy species besides downy brome to be reduced at either evaluation time in both runs, and salsify was reduced with three of the indaziflam combinations at 20 MAT in run 2 (Table 2.1,2.2).

Table 2.1. Downy brome and other dominant species cover in response to herbicide treatments over time. Run 1 established in 2017.

Treatment*	Rate	Dominant Species Cover† Downy Brome	Hooker's Balsamroot	Grey's Lomatium	Mule's Ear	Western Wheatgrass	Salsify	False Sunflower	Prickly Lettuce
	g ai/ha	%							
		2018							
Untreated	-	20.41 ab	31.37 d	1.89 de	9.05 abc	15.59 a	4.43 c-g	1.69 a-f	1.47 de
Indaziflam	102	3.79 d	34.72 cd	5.26 bcd	7.56 c	11.15 bcd	11.38 ab	3.38 a-e	0.00 g
Propoxycarbazone	59	13.27 c	30.52 d	4.20 bcd	10.53 abc	11.15 abc	5.07 c-h	1.05 b-f	3.36 cd
Rimsulfuron	70	1.69 e	32.61 cd	4.22 b-e	9.27 abc	11.16 ab	4.43 c-h	0.63 def	9.47 a
Imazapic	175	4.21 d	38.13 bcd	3.36 cde	9.89 abc	10.74 bcd	8.42 a-d	4.00 abc	5.89 ab
Glyphosate	210	0.63 ef	37.03 bcd	5.47 bc	10.51 abc	1.69 g	5.26 c-f	1.69 a-f	7.58 a
Indaz + propoxy	102 + 59	0.42 ef	37.68 bcd	6.52 b	10.32 abc	9.04 bcd	12.83 a	0.21 ef	0.42 efg
Indazi + rimsulf	102 + 70	0.00 f	31.80 cd	4.63 bcd	11.36 abc	9.69 bcd	3.58 d-i	5.71 abc	0.84 def
Indaz + imaz	102 + 175	0.42 ef	32.62 cd	5.67 bc	9.67 abc	2.11 fg	12.84 abc	6.11 a-d	1.05 d-g
Indaz + gly	102 + 210	0.00 f	37.69 bcd	12.00 a	12.84 ab	2.11 fg	5.04 c-f	2.12 b-f	0.63 efg
		2019							
Untreated	-	18.22 abc	40.04 bc	2.97 b-e	10.59 abc	8.47 bcd	1.48 f-i	1.91 a-f	1.91 de
Indaziflam	102	0.00 f	35.81 cd	4.66 bcd	8.26 bc	9.11 bcd	6.57 a-d	4.03 a-d	0.21 fg
Propoxycarbazone	59	20.34 ab	33.26 cd	4.45 bc	12.71 ab	7.20 cde	2.12 ghi	2.75 a-f	1.69 de
Rimsulfuron	70	15.47 bc	31.36 d	1.91 e	12.08 ab	6.78 de	1.27 hi	0.85 c-f	4.24 bc
Imazapic	175	18.43 abc	35.81 cd	1.27 e	11.65 abc	7.42 cde	1.48 i	4.24 a	5.72 ab
Glyphosate	210	23.09 a	40.25 bc	3.39 b-e	9.11 abc	0.64 g	1.91 e-i	1.48 a-f	1.91 cd
Indaz + propoxy	102 + 59	0.00 f	44.49 ab	5.72 bc	14.19 a	2.75 fg	5.93 b-e	0.00 f	0.00 g
Indazi + rimsulf	102 + 70	0.00 f	39.19 bcd	5.08 bc	8.90 bc	8.05 cde	1.06 i	6.14 a	0.00 g
Indaz + imaz	102 + 175	0.00 f	37.71 bcd	1.91 de	13.77 ab	4.03 ef	6.99 b-f	7.63 ab	0.00 g
Indaz + gly	102 + 210	0.00 f	52.75 a	5.51 bc	10.38 abc	1.91 fg	2.97 d-i	2.12 b-f	0.00 g

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

† Values labeled with the same letter within each column are not significantly different according to Fisher's protected LSD at p=0.05.

Table 2.2. Downy brome and other dominant species cover in response to herbicide treatments over time. Run 2 established in 2018.

Treatment*	Rate	Dominant Species Cover†															
		Downy Brome		Hooker's Balsamroot		Grey's Lomatium		Mule's Ear		Western Wheatgrass		Salsify		False Sunflower		Prickly Lettuce	
	g ai/ha	%															
		2019															
Untreated	-	36.65	a	22.67	g	4.24	b-e	4.03	e	10.17	ghi	3.60	c-f	1.91	gh	2.12	cd
Indaziflam	102	0.21	g	27.33	efg	5.51	bc	11.44	a	13.77	efg	10.81	a	12.08	abc	0.00	f
Propoxycarbazone	59	10.38	cd	27.33	efg	4.87	bcd	6.78	a-e	20.76	ab	4.24	c-f	4.87	d-h	3.39	bc
Rimsulfuron	70	1.91	fg	26.06	efg	3.39	b-f	11.23	a	18.64	bcd	0.21	f	9.11	bcd	4.87	ab
Imazapic	175	14.41	bc	32.84	a-f	3.60	b-f	4.66	e	12.71	fg	6.99	a-d	7.84	cde	5.93	a
Glyphosate	210	4.66	ef	33.69	a-e	5.93	b	8.47	a-e	4.87	jk	5.30	b-e	11.02	abc	1.91	cde
Indaz + propoxy	102 + 59	0.42	fg	28.39	c-g	5.72	bc	10.81	ab	16.74	b-f	10.81	a	3.60	e-h	0.42	def
Indazi + rimsulf	102 + 70	0.00	g	40.47	a	2.54	b-f	6.36	b-e	13.14	efg	0.64	ef	7.63	c-f	0.42	def
Indaz + imaz	102 + 175	0.00	g	27.54	d-g	3.18	b-f	7.84	a-e	8.05	hij	9.53	ab	1.91	gh	0.85	def
Indaz + gly	102 + 210	0.00	g	25.00	fg	9.75	a	7.42	a-e	2.97	k	7.84	abc	0.21	h	0.00	f
		2020															
Untreated	-	18.49	b	27.94	c-g	1.47	def	5.25	de	14.29	d-g	9.87	ab	3.36	e-h	1.05	def
Indaziflam	102	0.00	g	27.31	efg	2.73	b-f	11.34	a	12.61	fgh	10.29	a	15.13	a	0.00	f
Propoxycarbazone	59	9.24	d	29.83	b-g	1.05	ef	5.67	cde	25.21	a	6.93	a-d	6.72	c-g	0.21	ef
Rimsulfuron	70	7.98	de	28.36	c-g	1.05	ef	10.29	abc	19.75	bc	1.89	ef	7.77	cde	1.47	def
Imazapic	175	11.34	cd	34.45	a-e	0.42	f	5.46	de	12.61	fgh	6.93	a-d	9.45	bcd	1.47	def
Glyphosate	210	17.23	b	36.13	abc	1.47	def	7.56	a-e	6.72	ijk	1.89	ef	11.34	abc	0.00	f
Indaz + propoxy	102 + 59	0.00	g	33.19	a-f	2.31	c-f	9.87	a-d	17.44	b-e	7.14	a-d	1.89	gh	0.00	f
Indazi + rimsulf	102 + 70	0.00	g	37.82	ab	0.63	f	8.61	a-e	15.13	c-f	2.73	def	13.45	ab	0.00	f
Indaz + imaz	102 + 175	0.00	g	35.92	a-d	0.42	f	9.45	a-d	14.50	d-g	4.41	c-f	2.31	fgh	0.00	f
Indaz + gly	102 + 210	0.21	g	37.39	ab	5.04	bc	8.40	a-e	5.25	jk	3.99	c-f	0.00	h	0.00	f

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

† Values labeled with the same letter within each column are not significantly different according to Fisher's protected LSD at p=0.05.

Total weed cover remained unchanged with many treatments and was only reduced with treatments utilizing indaziflam in the first run 7 MAT. Similarly, overall native cover remained unchanged with most treatments, but was increased with indaziflam treatments. At 20 MAT, however, glyphosate alone increased weed cover and consequentially decreased native cover from the untreated control and compared to the previous year. Indaziflam combinations were the only treatments to maintain reductions in weed cover and increases in native plant cover at both evaluation times (Table 2.3). In run 2, weed cover was reduced and native cover was increased with every treatment except imazapic alone at 7 MAT. At 20 MAT, this trend only remained true for propoxycarbazone and the indaziflam combinations. Similar to the first run, glyphosate increased weed cover and decreased native cover compared to the untreated control and between evaluation times (Table 2.4).

Table 2.3. Percent cover of weeds and natives in response to herbicide treatments over time. Run 1 established in 2017.

		Cover†							
		Weed				Native			
Treatment*	Rate	7 MAT		20 MAT		7 MAT		20 MAT	
	g ai/ha	%							
Untreated	-	32.00	abc	27.33	bcd	68.00	def	72.67	cde
Indaziflam	175	21.70	de	25.21	bcd	78.30	bc	74.79	cde
Propoxycarbazone	59	32.43	abc	32.42	abc	67.57	def	67.58	def
Rimsulfuron	210	22.33	cde	34.53	ab	77.67	bcd	65.47	ef
Imazapic	70	25.26	bcd	34.53	ab	74.74	cde	65.47	ef
Glyphosate	102	26.33	bcd	38.77	a	73.67	cde	61.23	f
Indaz + propoxy	102 + 59	18.32	def	13.56	ef	81.68	abc	86.44	ab
Indaz + rimsulf	102 + 70	10.34	f	17.80	def	89.66	a	82.20	abc
Indaz + imaz	102 + 175	22.75	cde	21.40	de	77.25	bcd	78.60	bc
Indaz + gly	102 + 210	9.05	f	10.17	f	90.95	a	89.83	a

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

† Values labeled with the same letter within the two columns under each heading are not significantly different according to Fisher's protected LSD at p=0.05.

Table 2.4. Percent cover of weeds and natives in response to herbicide treatments over time. Run 2 established in 2018.

Treatment*	Rate	Cover† Weed 7 MAT		Weed 20 MAT		Native 7 MAT		Native 20 MAT	
	g ai/ha	%							
Untreated	-	48.73	a	37.18	bc	51.27	j	62.82	hi
Indaziflam	175	24.36	efg	31.09	cde	75.64	def	68.91	fgh
Propoxycarbazone	59	29.03	cdef	28.36	def	70.97	efgh	71.64	efg
Rimsulfuron	210	19.28	ghi	32.35	bcde	80.72	bcd	67.65	fghi
Imazapic	70	40.47	ab	35.50	bcd	59.53	ij	64.50	ghi
Glyphosate	102	28.81	def	40.13	b	71.19	efg	59.87	i
Indaz + propoxy	102 + 59	15.68	hij	14.50	hij	84.32	abc	85.50	abc
Indazi + rimsulf	102 + 70	8.69	j	26.05	efg	91.31	a	73.95	def
Indaz + imaz	102 + 175	12.29	ij	19.12	ghi	87.71	ab	80.88	bcd
Indaz + gly	102 + 210	8.05	j	21.64	fgh	91.95	a	78.36	cde

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

† Values labeled with the same letter within the two columns under each heading are not significantly different according to Fisher's protected LSD at p=0.05.

Total species richness was reduced in treatments including indaziflam at all evaluation times in both runs, but this decrease was related to reductions in number of weed species. Weed species richness was reduced in all indaziflam treatments at both observation times, but native species richness was similar to the untreated for all treatments at 7 MAT in the first run, and at 20 MAT in the second run (Table 2.5,2.6). In the second run, total richness was reduced in every treatment except rimsulfuron and glyphosate alone at 7 MAT (Table 2.6). This reduction in total richness can be accounted for by similar reductions in weed richness for the same treatments; native richness was unchanged for all treatments. Native richness did not differ from 7 MAT to 20 MAT for most treatments but increased in the untreated control and with rimsulfuron alone in the first run, and decreased with glyphosate in the second run (Table 2.5,2.6).

Table 2.5. Total plant community species richness; weed richness and native richness in response to herbicide treatments. Run 1 established in 2017.

Treatment*	Rate	Total Richness† 7 MAT		Total Richness† 20 MAT		Weed Richness† 7 MAT		Weed Richness† 20 MAT		Native Richness† 7 MAT		Native Richness† 20 MAT	
	g ai/ha	#											
Untreated	-	10.5	efg	13.75	ab	5	cd	6	b	5.5	cde	7.75	a
Indaziflam	175	9.25	fghi	9.5	fghi	3.75	ef	4.25	de	5.5	cde	5.25	cde
Propoxycarbazone	59	12.25	bcd	13.25	abc	5.75	bc	5.5	bc	6.5	abc	7.75	a
Rimsulfuron	210	10.75	def	13.5	ab	6	b	6.25	b	4.75	e	7.25	ab
Imazapic	70	11.75	cde	12.25	bcd	5.75	bc	5.75	bc	6	bcde	6.5	abc
Glyphosate	102	12.25	bcd	14.5	a	6	b	8	a	6.25	bcd	6.5	abc
Indaz + propoxy	102 + 59	9	ghi	9	ghi	3	fg	3.5	efg	6	bcde	5.5	cde
Indazi + rimsulf	102 + 70	8	i	8.75	hi	3	fg	3	fg	5	de	5.75	cde
Indaz + imaz	102 + 175	8.5	i	10.25	efgh	3.25	fg	3.75	ef	5.25	cde	6.5	abc
Indaz + gly	102 + 210	8.25	i	8.75	hi	2.75	g	3.25	fg	5.5	cde	5.5	cde

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

† Values labeled with the same letter within the two columns under each heading are not significantly different according to Fisher's protected LSD at p=0.05.

Table 2.6. Total plant community species richness; weed richness and native richness in response to herbicide treatments. Run 2 established in 2018.

Treatment[*]	Rate	Total Richness[†]				Weed Richness[†]				Native Richness[†]			
		7 MAT		20 MAT		7 MAT		20 MAT		7 MAT		20 MAT	
	g ai/ha	#											
Untreated	-	11.5	bc	11.5	bc	5.25	bc	5.75	abc	6.25	ab	5.75	abcd
Indaziflam	175	8.5	def	8.75	def	2.5	efg	3.75	de	6	abc	5	bcd
Propoxycarbazone	59	11.5	bc	11.25	bc	5.5	abc	6	ab	6	abc	5.25	bcd
Rimsulfuron	210	9.25	de	12	ab	3.5	def	6.5	ab	5.75	abcd	5.5	bcd
Imazapic	70	9.5	de	10	cd	4.5	cd	5.5	abc	5	bcd	4.5	d
Glyphosate	102	13.25	a	11.75	ab	6.25	ab	6.75	a	7	a	5	bcd
Indaz + propoxy	102 + 59	8	ef	8.5	def	2.75	ef	3	ef	5.25	bcd	5.5	bcd
Indazi + rimsulf	102 + 70	5.75	h	7.25	fgh	1	h	2.75	ef	4.75	cd	4.5	d
Indaz + imaz	102 + 175	7.25	fgh	7.5	fg	2.25	fgh	2.75	ef	5	bcd	4.75	cd
Indaz + gly	102 + 210	6	gh	8	ef	1.25	gh	2.75	ef	4.75	cd	5.25	bcd

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

[†] Values labeled with the same letter within the two columns under each heading are not significantly different according to Fisher's protected LSD at p=0.05.

In both runs at 7 MAT, diversity scores were only reduced in two treatments: indaziflam + rimsulfuron and indaziflam + glyphosate. Diversity generally did not change between evaluation times; it only increased in the second run with indaziflam + rimsulfuron. Evenness remained largely unchanged within respective observation times but was reduced from 7 MAT to 20 MAT with all treatments including glyphosate in the first run (Table 2.7, 2.8).

Table 2.7. Diversity scores and evenness in response to herbicide treatments over time. Run 1 established in 2017.

Treatment*	Rate	Diversity†‡				Evenness†			
		7 MAT		20 MAT		7 MAT		20 MAT	
	g ai/ha								
Untreated	-	1.81	abcde	1.81	abcde	0.77	ab	0.70	cde
Indaziflam	175	1.71	defg	1.73	cdef	0.77	ab	0.77	abc
Propoxycarbazone	59	2.01	a	1.93	abc	0.81	a	0.75	abcd
Rimsulfuron	210	1.78	bcde	1.98	ab	0.75	abcd	0.76	abcd
Imazapic	70	1.81	abcde	1.88	abcd	0.74	abcde	0.75	abcd
Glyphosate	102	1.86	abcd	1.80	bcde	0.75	abcd	0.67	ef
Indaz + propoxy	102 + 59	1.62	efgh	1.50	hi	0.74	abcde	0.68	de
Indazi + rimsulf	102 + 70	1.57	fgh	1.62	efgh	0.76	abcd	0.74	abcde
Indaz + imaz	102 + 175	1.63	efgh	1.62	efgh	0.77	ab	0.70	bcde
Indaz + gly	102 + 210	1.51	ghi	1.30	i	0.72	bcde	0.60	f

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

† Values labeled with the same letter within the two columns under each heading are not significantly different according to Fisher's protected LSD at p=0.05.

‡ Diversity scores were calculated according to Shannon's diversity equation.

Table 2.8. Diversity scores and evenness in response to herbicide treatments over time. Run 2 established in 2018.

		Diversity†‡				Evenness†			
Treatment*	Rate	7 MAT		20 MAT		7 MAT		20 MAT	
	g ai/ha								
Untreated	-	1.75	bcdef	1.87	abc	0.72	bc	0.77	abc
Indaziflam	175	1.66	defg	1.76	bcde	0.79	ab	0.82	a
Propoxycarbazone	59	1.94	ab	1.79	bcde	0.79	ab	0.74	abc
Rimsulfuron	210	1.77	bcde	1.95	ab	0.80	a	0.79	ab
Imazapic	70	1.84	abcd	1.80	bcd	0.82	a	0.79	ab
Glyphosate	102	2.01	a	1.87	abc	0.78	abc	0.76	abc
Indaz + propoxy	102 + 59	1.67	cdefg	1.65	defg	0.81	a	0.77	abc
Indazi + rimsulf	102 + 70	1.22	i	1.49	gh	0.70	c	0.75	abc
Indaz + imaz	102 + 175	1.59	efgh	1.56	fgh	0.81	a	0.78	ab
Indaz + gly	102 + 210	1.43	hi	1.55	fgh	0.80	a	0.75	abc

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

† Values labeled with the same letter within the two columns under each heading are not significantly different according to Fisher's protected LSD at p=0.05.

‡ Diversity scores were calculated according to Shannon's diversity equation.

Discussion

In this study, indaziflam was especially effective in controlling downy brome and was observed to have the longest residual of the tested herbicides. Indaziflam was the only herbicide that controlled downy brome for more than one year. A similar study was conducted by Clark and colleagues (2019) in which comparable results were observed. In their study, downy brome cover was significantly reduced from untreated controls with every indaziflam treatment at rates of 73 g ai/ha or higher (Clark *et al.* 2019). Other herbicides were not as effective at controlling downy brome or maintaining or raising native species cover (Clark *et al.* 2019). The cover of perennial grasses in our study was more sparse than the study conducted by Clark *et al.*; where they found no change or increase in perennial grass cover for all treatments, in our study, there were several treatments in the first run where the dominant perennial grass species, western wheatgrass (*Pascopyrum smithii*) was reduced. However, in two of the four treatments where wheatgrass was reduced 20 MAT in the first run, overall native cover increased compared to the untreated. Significant reduction of perennial grass with indaziflam is inconsistent with results found in previous studies (Sebastian *et al.* 2017b, Clark *et al.* 2019). This could be due to the fact that western wheatgrass cover in the untreated plots of run 1 was initially much higher than that of other plots.

A previous study measuring species richness in response to indaziflam and imazapic treatments with or without glyphosate burndown shows no change in richness across all treatments and timings (Sebastian *et al.* 2017b). In our study, in plots where reductions in total richness was observed 7 MAT, it was always due to reductions in weed richness. Native richness either remained unchanged or increased between years for all herbicide treatments. In the first run, 20 MAT, indaziflam + glyphosate increased Hooker's balsamroot (*Balsamorhiza hookeri*), one of the dominant native forbs, more than any other treatment. Sebastian *et al.* (2017b) found that indaziflam with a glyphosate burndown increased overall forb cover. Along with an increase in balsamroot, indaziflam + glyphosate recorded the highest numerical means for native species cover across all runs and evaluation times. Across all plots, total weed cover did not exceed total native species cover.

Indaziflam combination treatments all had among the highest means for native species cover at each evaluation time for both runs. These treatments were also among the highest and lowest for native species richness and weed species richness, respectively. Because of the reduction of weed species richness, the indaziflam combinations also showed among the lowest means for total species richness, and consequentially, diversity scores. At 20 MAT in the first run, only two of the four combination treatments had scores that were not significantly different from the untreated.

This study shows that opening the canopy without residual herbicidal control can increase annual weed cover. Downy brome was able to outcompete and outlast many of the broadleaf weeds present on the site; thus, it is imperative to consider treatments carefully when a site is even moderately infested with downy brome. Herbicides with residual activity used in combination with herbicides with little to no residual activity can push back annual weeds for more than one year and allow resurgence of native or desirable perennial vegetation.

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CHAPTER III

VENTENATA CONTROL AND PLANT COMMUNITY RESPONSE TO HERBICIDE TREATMENTS

Abstract

Ventenata is a highly invasive annual grass native to Eurasia and North Africa that has been a problem in the western United States for the past decade and has only recently been discovered in Utah. This project was designed to test the efficacy of various herbicides alone and in combination with indaziflam on ventenata, and to measure plant community response. Two trials were established near Mt. Sterling, Utah, one in 2017 and another in 2018 with some adjustments to treatments in 2018. Herbicides were applied to 6 by 18 m plots arranged in a randomized complete block design replicated four times. Species cover was evaluated using point-line-intercept transects, recording a point every 15 cm. In 2017, only treatments including rimsulfuron or indaziflam controlled ventenata in the first year, reducing cover to less than 1%. In the second year, ventenata cover increased in seven of eleven treatments including three of the five indaziflam treatments. Glyphosate and imazapic alone were less effective than rimsulfuron. Wild onion increased in four of five of the indaziflam treatments excluding indaziflam + rimsulfuron; likewise, overall species richness increased in four of the five excluding glyphosate + indaziflam at the highest rate. Richness was only decreased with imazapic alone. Three of the indaziflam combinations increased total broadleaf cover, but this included increases of bindweed in some plots. The 2018 trial largely mirrored the

2017 trial. In both trials, aminopyralid nearly doubled ventenata cover due to reductions in broadleaf plants. Annual grass suppression for more than one year allows resurgence of desirable and weedy perennial plants. This project provides understanding on how herbicide treatments and combinations affect plant community dynamics in systems invaded by ventenata. A greenhouse study was established alongside the field study to test the efficacy of three herbicides: rimsulfuron, imazapic, and glyphosate at increasing rates on three invasive annual grasses: ventenata, medusahead, and downy brome in a controlled environment. Two runs were conducted with four replicates for each treatment. Rimsulfuron reduced dry biomass of all grasses at the most rates. Glyphosate was most ineffective out of all the treatments; however, ventenata proved to be much more sensitive to glyphosate in the greenhouse than in the field. This study suggests that timing in the field contributes to overall herbicide effectiveness just as much as, if not more than physiological response.

Introduction

Ventenata dubia (Leers) Coss is an exotic winter annual grass in the *Aveneae* tribe native to Eurasia and North Africa (Wallace *et al.* 2015; Alomran *et al.* 2019). Common names include ventenata, North Africa grass, and wiregrass (Wallace *et al.* 2015; Fryer 2017). It is a relatively new invader in the western United States that has only been a significant problem since about the mid-2000s (Wallace and Prather 2016). Near the beginning of its invasion in 2001, its spread rate was over one million hectares per year and it is likely that the plant will continue to spread at an alarming rate (Jones *et al.*

2018). As of now, ventenata populations have been reported in Oregon, Montana, Utah, and Wyoming, and it has been reported to still be in an early stage of invasion (Jones *et al.* 2017, 2018; Koby *et al.* 2019). Ventenata is an aggressive invader that is able to displace stands of both downy brome and medusahead, two other invasive annual grasses (Jones *et al.* 2018). Ventenata has a relatively high silica content: about 9% or more of its dry biomass, rendering it unpalatable to livestock (Mangold *et al.* 2019; S. Clark, personal communication, March 5, 2020). Small farm owners with ventenata-infested pastures have reported forage losses of up to 75% following invasion (Wallace and Prather 2011). In rangeland settings, ventenata has no trouble displacing desirable vegetation due to its extensive, shallow root system and litter that retains soil moisture for its germinating seedlings (Wallace and Prather 2016; Fryer 2017; Harvey *et al.* 2019).

Because of its recent invasion, there is a limited pool of studied control methods for ventenata. A few of the most commonly used herbicides to control ventenata are rimsulfuron, imazapic, and indaziflam (Brummer *et al.* 2012; Wallace and Prather 2016; Davies and Hamerlynck 2019; Koby *et al.* 2019). Rimsulfuron and imazapic are both acetolactase synthase (ALS) inhibiting compounds, the former in the sulfonylurea chemical family and the latter in the imidazolinone chemical family (Tu *et al.* 2001; Ahmad 2019). Indaziflam is a recently released cellulose biosynthesis inhibitor (CBI) that, unlike previous CBI herbicides, has strong activity on monocots as well as eudicots (Brabham *et al*. 2014). It is also capable of suppressing annual grasses for up to three years or more, whereas rimsulfuron and imazapic only consistently provide one year of control (Sebastian *et al.* 2016; Clark *et al.* 2019). To date, there have been no published studies of ventenata control in Utah.

Materials and Methods

Field Study. A site was chosen near Mt. Sterling, Utah (41˚34’38.65” N, 111˚54’35.01” W; 1601 m elevation) that is infested with ventenata. The experiment was organized in a randomized complete block design with 11 herbicide treatments at different timings, and two runs established on the same site, one in 2017 (Run 1) and another in 2018 (Run 2). Treatments were adjusted for the 2018 trial. Individual plots were replicated four times and measured 3 meters by 9 meters. Treatments applied in both trials are as follows: applied in September (early fall) of 2017 and 2018 for runs 1 and 2, respectively, indaziflam at 73 g ai/ha; and applied in November (fall) of 2017 and 2018 for runs 1 and 2, respectively, imazapic at 175 g ai/ha, glyphosate at 210 g ai/ha, rimsulfuron at 52.5 g ai/ha, indaziflam at 73 g ai/ha plus imazapic at 175 g ai/ha, indaziflam at 73 g ai/ha plus glyphosate at 210 g ai/ha, and indaziflam at 73 g ai/ha plus rimsulfuron 52.5 g ai/ha. Treatments applied only in the 2017 trial include aminopyralid at 123 g ai/ha, quinclorac at 420 g ai/ha, and imazapic at 105 g ai/ha applied in May (spring) and, indaziflam at 102 g ai/ha plus glyphosate at 210 g ai/ha applied in November. Treatments unique to the 2018 trial are aminopyralid at 123 g ai/ha, indaziflam at 44 g ai/ha, and imazapic at 105 g ai/ha applied in September and indaziflam at 73 g ai/ha plus imazapic at 105 g ai/ha applied in November. All treatments were applied with a CO_2-pressurized backpack sprayer calibrated to deliver 234 L/ha at 276 kPa and all treatments included a non-ionic surfactant at 0.25% v/v.

Plots were evaluated visually for percent control of ventenata each spring following treatment for two years. Likewise, plots were evaluated for percent cover of species present in early summer using the point-line intercept method (Elzinga *et al* 1998) along transect lines with a point recorded every 15 cm. Transect tapes were run lengthwise through the center of each plot. Transect data were transformed using an arcsine square root transformation. All data were analyzed using general linear model or repeated measure ANOVA. Diversity and evenness were calculated using the Shannon-Weiner diversity equation (Shannon 1948).

Greenhouse Study. Based on our observations, glyphosate and imazapic are less effective when used to manage ventenata than when used on medusahead or downy brome in field settings. A greenhouse study was designed to test the efficacy of glyphosate and imazapic on ventenata, compared with medusahead and downy brome. The study was designed as a randomized complete block with 25 treatments, replicated four times. For each of the three species, 20 seeds were planted in 10 cm x 10 cm x 10 cm pots in a 50/50 mix of peat moss and vermiculite. Greenhouse conditions included artificial lighting set to 16 hours per day, with temperatures ranging from 23-26°C. Plants were watered to saturation daily. Ventenata was seeded about three weeks before the others due to its slower emergence and growth. All treatments included a non-ionic surfactant and were applied about 2.5 weeks after the latest planting date using an enclosed research track sprayer with an 8002 flat fan nozzle calibrated to deliver 187 L/ha at 207 kPa. Herbicide treatments were as follows: glyphosate at 630 g ai/ha, 315 g ai/ha, 157.5 g ai/ha, 78.75 g ai/ha, 39.38 g ai/ha, 19.69 g ai/ha, 9.84 g ai/ha, and 4.92 g ai/ha; imazapic at 210 g ai/ha, 105 g ai/ha, 52.5 g ai/ha, 26.25 g ai/ha, 13.13 g ai/ha, 6.56 g ai/ha, 3.28 g ai/ha, and 1.64 g ai/ha; and rimsulfuron at 52.5 g ai/ha, 26.25 g ai/ha, 13.13 g ai/ha, 6.56 g ai/ha, 3.28 g ai/ha, 1.64 g ai/ha, and 0.82 g ai/ha. Past studies conclude that rimsulfuron provides high ventenata control; thus, it was included as a comparison (Wallace and Prather 2016; Koby *et al.* 2019). A second run of the experiment was carried out just after the first run.

Pots were evaluated visually for percent control and measured for maximum height. After 28 days from the treatment date, all plants were harvested for aboveground biomass, dried, and weighed. Data were analyzed using general linear model or repeated measure ANOVA. Dry weight data were fit to a 3-parameter logistic dose response model [Equation 1]:

$$Y = \frac{a}{1} + \left(\frac{x}{x_0}\right)^b \qquad [1]$$

in which a represents the maximum, x represents a given herbicide rate, x_0 represents the EC_{50} value (the rate at which biomass is reduced by 50%), and b represents the slope at x_0.

Results

Field Study. Overall ventenata cover was reduced from the untreated control with all treatments including indaziflam for all evaluation times in the first run and at 7 MAT in the second (Table 3.1). Due to a drought in run two, ventenata cover was significantly less at 20 MAT than at 7 MAT, which impacted the ability to measure differences in cover among treatments. Aminopyralid increased ventenata cover for every evaluation except 20 MAT in run two (Table 3.3). In the first run, ventenata cover increased from 7 MAT to 20 MAT with imazapic, glyphosate, and rimsulfuron, as well as three out of the five indaziflam treatments (Table 3.1). In run two, ventenata cover did not increase between evaluations with any treatment (Table 3.3). Japanese brome was reduced with most treatments except imazapic in the first run 20 MAT, and in the second run at both evaluation times (Table 3.1, 3.3). In the first run, perennial grass cover decreased from 7 to 20 MAT with nine out of the eleven herbicide treatments, whereas in the second run, perennial grass cover increased between evaluation times with nine of the herbicide treatments (Table 3.1, 3.3). Prickly lettuce cover did not change for most treatments in both runs between evaluation times. Wild onion, a native, increased from 7 to 20 MAT with only three treatments; each including indaziflam in the first run and decreased with five treatments in the second run, four including indaziflam (Table 3.2, 3.4). A new species, western aster, appeared at high levels of cover in many of the treatments in which wild onion decreased (Table 3.4).

Table 3.1. Ventenata and other dominant grasses cover in response to herbicide treatments over time. Run 1 established in 2017.

Treatment[*]	Rate	Timing	Dominant Species Cover[†] Ventenata 2018		Ventenata 2019		Japanese brome 2018		Japanese brome 2019		Perennial grass[‡] 2018		Perennial grass[‡] 2019	
	g ai/ha		%											
Untreated	-	-	33.9	fg	57.5	cde	9.6	a	4.9	b	11.6	e-j	3.5	jk
Indaziflam	44	Early Fall	66.2	abc	72.8	ab	0.3	de	1.3	cde	15.9	c-h	4.8	ijk
Indaziflam	73	Early Fall	45.8	def	60.3	bcd	0.3	de	0.1	de	23.3	bc	7.6	hijk
Aminopyralid	123	Early Fall	22.3	ghi	62.3	abc	1.8	bcd	2.6	bc	22.0	bcd	6.5	ijk
Imazapic	105	Early Fall	0.1	j	17.5	hi	0.0	e	0.6	cde	22.4	bcd	4.8	ijk
Imazapic	175	Fall	25.8	gh	78.9	a	0.3	de	0.1	de	13.4	d-i	2.2	k
Glyphosate	210	Fall	42.8	ef	72.4	abc	1.0	b-e	0.3	cde	10.8	f-k	3.9	jk
Rimsulfuron	52.5	Fall	0.3	j	61.4	bc	1.6	b-e	0.1	de	34.5	a	9.6	f-k
Indaz + imaz	73+175	Fall	0.0	j	30.3	hi	0.3	cde	0.0	e	18.5	c-f	10.9	f-k
Indaz + gly	73+210	Fall	0.0	j	14.5	hij	0.0	e	0.6	cde	29.7	ab	10.1	f-k
Indaz + rim	73+52.5	Fall	0.0	j	20.6	ghi	0.0	e	0.0	e	17.7	c-g	7.9	h-k
Indaz + imaz	73+105	Fall	0.0	j	11.8	ij	0.0	e	0.0	e	20.7	b-e	8.8	g-k

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

[†] Values labeled with the same letter within each species are not significantly different according to Fisher's protected LSD at p=0.05.

[‡] Perennial grasses included intermediate wheatgrass (*Thinopyrum intermedium*) and smooth brome (*Bromus inermis*).

Table 3.2. Prickly lettuce and wild onion cover in response to herbicide treatments over time. Run 1 established in 2017.

Treatment[*]	Rate	Timing	Dominant Species Cover[†]							
			Prickly lettuce				Wild onion			
			2018		2019		2018		2019	
	g ai/ha		%							
Untreated	-	-	6.0	bc	2.2	bc	0.0	f	0.0	f
Indaziflam	44	Early Fall	0.4	c	0.4	c	0.0	f	0.9	ef
Indaziflam	73	Early Fall	1.7	bc	0.4	c	0.3	f	1.3	def
Aminopyralid	123	Early Fall	19.4	a	1.3	bc	1.4	b-f	0.0	f
Imazapic	105	Early Fall	2.2	bc	1.8	bc	1.0	c-f	7.4	a
Imazapic	175	Fall	6.9	b	0.0	c	2.0	a-e	0.0	f
Glyphosate	210	Fall	3.9	bc	0.0	c	1.0	c-f	0.4	f
Rimsulfuron	52.5	Fall	4.7	bc	0.9	bc	0.7	c-f	0.4	f
Indaz + imaz	73+175	Fall	6.9	b	3.1	bc	1.0	c-f	4.4	abc
Indaz + gly	73+210	Fall	3.9	bc	2.2	bc	0.7	ef	4.8	a-d
Indaz + rim	73+52.5	Fall	2.2	bc	3.1	bc	0.6	def	0.4	f
Indaz + imaz	73+105	Fall	0.0	c	0.0	c	1.4	c-f	5.7	ab

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

[†] Values labeled with the same letter within each species are not significantly different according to Fisher's protected LSD at p=0.05.

Table 3.3. Ventenata and other dominant grasses cover in response to herbicide treatments over time. Run 2 established in 2018.

Treatment*	Rate	Timing	Dominant Species Cover†											
			Ventenata				Japanese brome				Perennial grass‡			
			2019		2020		2019		2020		2019		2020	
	g ai/ha		%											
Untreated	-	-	28.1	bcd	8.6	fg	13.2	cde	25.9	a	4.8	i	16.4	c-g
Indaziflam	44	Early Fall	1.3	g	0.0	g	2.2	ghi	1.3	hi	11.4	e-i	22.0	abc
Indaziflam	73	Early Fall	0.0	g	0.4	g	1.3	hi	0.4	i	5.7	i	29.3	ab
Aminopyralid	123	Early Fall	46.9	a	15.5	ef	7.0	e-h	14.7	bcd	10.5	f-i	22.4	abc
Imazapic	105	Early Fall	14.5	ef	18.1	def	8.8	d-g	9.9	c-f	12.3	d-i	22.0	abc
Imazapic	175	Fall	35.6	b	23.7	cde	4.0	f-i	20.7	ab	5.3	i	12.9	d-i
Glyphosate	210	Fall	35.5	b	34.1	bc	3.5	f-i	15.9	bc	7.5	hi	18.5	c-f
Rimsulfuron	52.5	Fall	2.2	g	16.8	ef	2.2	ghi	10.8	cde	20.2	cde	30.2	a
Indaz + imaz	73+175	Fall	0.0	g	0.9	g	1.3	hi	0.9	hi	5.3	i	20.7	bcd
Indaz + gly	73+210	Fall	0.0	g	0.0	g	0.0	i	0.0	i	15.4	c-h	22.0	abc
Indaz + rim	73+52.5	Fall	0.0	g	0.0	g	0.0	i	0.0	i	18.0	c-g	17.7	c-g
Indaz + imaz	73+105	Fall	0.0	g	0.0	g	0.0	i	0.0	i	9.6	ghi	20.3	cd

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

† Values labeled with the same letter within each species are not significantly different according to Fisher's protected LSD at p=0.05.

‡ Perennial grasses included intermediate wheatgrass (*Thinopyrum intermedium*) and smooth brome (*Bromus inermis*).

Table 3.4. Prickly lettuce, wild onion, and western aster cover in response to herbicide treatments over time. Run 2 established in 2018.

Treatment[*]	Rate	Timing	Dominant Species Cover[†]											
			Prickly lettuce				Wild onion				Western aster			
			2019		2020		2019		2020		2019		2020	
	g ai/ha		%											
Untreated	-	-	1.3	d	0.4	d	2.6	e-h	2.2	e-h	9.2	d-h	17.7	a-d
Indaziflam	44	Early Fall	1.3	d	0.0	d	11.4	abc	3.9	d-h	7.5	e-h	9.1	d-h
Indaziflam	73	Early Fall	1.3	d	0.0	d	5.7	d-g	6.0	def	12.7	b-f	13.4	b-f
Aminopyralid	123	Early Fall	0.9	d	3.0	cd	0.0	h	0.4	gh	2.2	gh	14.7	b-f
Imazapic	105	Early Fall	1.8	cd	0.0	d	2.2	e-h	1.7	e-h	15.4	b-e	27.2	a
Imazapic	175	Fall	3.1	cd	0.9	d	3.5	d-h	1.7	e-h	10.6	c-g	10.8	c-g
Glyphosate	210	Fall	0.4	d	0.0	d	8.3	bcd	1.3	fgh	0.4	h	6.5	e-h
Rimsulfuron	52.5	Fall	10.1	ab	2.2	cd	1.8	e-h	1.3	fgh	5.3	fgh	2.2	gh
Indaz + imaz	73+175	Fall	6.6	bc	0.0	d	12.3	ab	3.0	e-h	12.7	b-f	17.7	a-d
Indaz + gly	73+210	Fall	1.3	d	0.0	d	16.3	a	6.9	cde	0.9	h	0.9	h
Indaz + rim	73+52.5	Fall	0.9	d	0.0	d	4.8	d-g	3.9	d-h	11.8	c-g	9.9	c-h
Indaz + imaz	73+105	Fall	12.7	a	0.0	d	12.7	ab	6.0	def	19.3	abc	21.6	ab

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

[†] Values labeled with the same letter within each species are not significantly different according to Fisher's protected LSD at p=0.05.

In the first run, 7 MAT, species richness did not differ from the untreated control for any treatment; however, at 20 MAT, richness increased compared to the untreated in three out of five indaziflam treatments and increased from the previous evaluation in four (Table 3.5). Richness only decreased between evaluation times with imazapic at 175 g ai/ha (Table 3.5). In the second run at 7 MAT, richness decreased compared to the untreated control with all treatments including indaziflam and at 20 MAT, richness was reduced with only two treatments (Table 3.6). Richness only decreased between evaluation times with indaziflam (44 g ai/ha) and the untreated (Table 3.6).

Table 3.5. Plant community species richness response to herbicide treatments over time. Run 1 established in 2017.

Treatment*	Rate	Timing	Richness†			
			7 MAT		20 MAT	
	g ai/ha		#			
Untreated	-	-	7	a-d	6.5	bcd
Aminopyralid	123	Spring	4.75	d	6.5	bcd
Quinclorac	420	Spring	6.75	a-d	7.5	a-d
Imazapic	105	Spring	7.75	abc	6.5	bcd
Indaziflam	73	Early Fall	6.5	bcd	9.5	a
Imazapic	175	Fall	8.75	ab	5.25	cd
Glyphosate	210	Fall	7.25	a-d	5.5	cd
Rimsulfuron	52.5	Fall	6.25	bcd	6.25	bcd
Indaz + imaz	73+175	Fall	6	bcd	9.5	a
Indaz + gly	73+210	Fall	6.25	bcd	9.5	a
Indaz + rim	73+52.5	Fall	4.75	d	8	abc
Indaz + gly	102+210	Fall	7	a-d	6.5	bcd

* 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 protected LSD at p=0.05.

Table 3.6. Plant community species richness response to herbicide treatments over time. Run 2 established in 2018.

Treatment*	Rate	Timing	Richness†			
			7 MAT		20 MAT	
	g ai/ha		#			
Untreated	-	-	11.5	a	9.25	b-f
Aminopyralid	123	Early Fall	6.75	hij	7.5	f-j
Indaziflam	44	Early Fall	11	ab	9	c-f
Imazapic	105	Early Fall	9.75	a-e	9	c-f
Indaziflam	73	Early Fall	9	c-f	8.5	d-h
Imazapic	175	Fall	9.75	a-e	9.5	b-e
Glyphosate	210	Fall	10	a-d	8.25	d-i
Rimsulfuron	52.5	Fall	10.5	abc	9.75	a-e
Indaz + imaz	73+175	Fall	9	c-f	8.25	d-i
Indaz + gly	73+210	Fall	8	e-j	8.25	d-i
Indaz + rim	73+52.5	Fall	6.5	ij	6.25	j
Indaz + imaz	73+105	Fall	8.75	c-g	7	g-j

* 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 protected LSD at p=0.05.

Diversity scores in the first run remained largely unchanged from the untreated at 7 MAT, only decreasing with aminopyralid. At 20 MAT, diversity increased from the untreated with four of the five indaziflam treatments, excluding indaziflam (102 g ai/ha) + glyphosate (210 g ai/ha), and decreased with imazapic. Between evaluation times, diversity increased with three of the five treatments containing indaziflam and decreased with imazapic at both rates and with glyphosate (Table 3.7). In the second run at 7 MAT, diversity was not different from the untreated with any treatment, but decreased with aminopyralid, imazapic (175 g ai/ha), and two of the indaziflam combinations. Between evaluation times, diversity decreased with indaziflam at 44 g ai/ha (Table 3.8). In the first run at 7 MAT, evenness remained unchanged from the untreated. At 20 MAT in the first run, evenness decreased with aminopyralid, imazapic at both rates, and glyphosate, while it increased with two of the indaziflam combinations (Table 3.7). Evenness was not different among treatments in the second run either within or between evaluation times (Table 3.8).

Table 3.7. Diversity scores and evenness in response to herbicide treatments over time. Run 1 established in 2017.

			Diversity†‡				Evenness†			
Treatment*	Rate	Timing	7 MAT		20 MAT		7 MAT		20 MAT	
	g ai/ha									
Untreated	-	-	1.51	b-f	1.27	e-i	0.78	a-d	0.67	c-f
Aminopyralid	123	Spring	0.93	hij	0.92	hij	0.66	c-f	0.49	gh
Quinclorac	420	Spring	1.35	c-g	1.18	f-i	0.74	a-e	0.59	e-h
Imazapic	105	Spring	1.66	a-e	1.11	g-j	0.82	abc	0.59	e-h
Indaziflam	73	Early Fall	1.35	c-g	1.84	ab	0.74	a-e	0.82	abc
Imazapic	175	Fall	1.74	abc	0.76	j	0.81	abc	0.47	h
Glyphosate	210	Fall	1.51	b-f	0.88	ij	0.77	a-d	0.53	fgh
Rimsulfuron	52.5	Fall	1.55	a-f	1.16	f-j	0.85	ab	0.63	d-g
Indaz + imaz	73+175	Fall	1.40	c-g	1.70	a-d	0.79	a-d	0.75	a-e
Indaz + gly	73+210	Fall	1.23	f-i	1.94	a	0.70	b-e	0.87	a
Indaz + rim	73+52.5	Fall	1.22	f-i	1.73	abc	0.78	a-d	0.84	ab
Indaz + gly	102+210	Fall	1.31	d-h	1.50	b-f	0.68	c-f	0.87	a

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

† Values labeled with the same letter within the two columns under each heading are not significantly different according to Fisher's protected LSD at p=0.05.

‡ Diversity scores were calculated according to Shannon's diversity equation.

Table 3.8. Diversity scores and evenness in response to herbicide treatments over time. Run 2 established in 2018.

Treatment*	Rate	Timing	Diversity†‡ 7 MAT		Diversity†‡ 20 MAT		Evenness† 7 MAT		Evenness† 20 MAT	
	g ai/ha									
Untreated	-	-	2.05	ab	1.79	a-f	0.84	a-d	0.81	a-d
Aminopyralid	123	Early Fall	1.41	g	1.62	d-g	0.75	d	0.81	a-d
Indaziflam	44	Early Fall	2.08	a	1.78	b-f	0.87	a	0.81	a-d
Imazapic	105	Early Fall	1.85	a-d	1.67	c-g	0.81	a-d	0.76	cd
Indaziflam	73	Early Fall	1.78	b-f	1.66	c-g	0.81	a-d	0.77	a-d
Imazapic	175	Fall	1.71	c-f	1.88	a-d	0.75	cd	0.84	a-d
Glyphosate	210	Fall	1.76	b-f	1.66	d-g	0.77	bcd	0.80	a-d
Rimsulfuron	52.5	Fall	1.95	abc	1.78	b-f	0.85	abc	0.78	a-d
Indaz + imaz	73+175	Fall	1.84	a-e	1.69	c-g	0.84	a-d	0.81	a-d
Indaz + gly	73+210	Fall	1.73	c-f	1.66	c-g	0.83	a-d	0.80	a-d
Indaz + rim	73+52.5	Fall	1.55	efg	1.54	fg	0.83	a-d	0.84	a-d
Indaz + imaz	73+105	Fall	1.84	a-d	1.64	d-g	0.86	ab	0.87	ab

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

† Values labeled with the same letter within the two columns under each heading are not significantly different according to Fisher's protected LSD at p=0.05.

‡ Diversity scores were calculated according to Shannon's diversity equation.

Greenhouse Study. In the greenhouse trials, differences in plant response during the two runs influenced results. The largest difference was that ventenata produced less biomass in Run 2 than it did in Run1. With different growth rates between species, biomass is converted to a percentage of the untreated in charts showing differences between the species when treated with the same herbicide. When comparing the response of a single species to the three herbicides, the actual biomass is used and the rate scale is converted to a percentage of the field use rate, as use rates vary widely among the herbicides tested. Non-linear regression curves effectively depict the response of the three grass species to the three herbicides evaluated.

Rimsulfuron provided the best overall control of all the herbicides regarding species dry biomass. It reduced dry biomass for every species at most rates (Figure 3.3). Glyphosate provided the least noticeable control of all three species, reducing biomass with only the highest two or three rates (Figure 3.1). Imazapic moderately controlled all grasses (Figure 3.2). Of all the grasses, glyphosate was most effective on ventenata (Figure 3.6). Rimsulfuron and imazapic nearly equally controlled medusahead (Figure 3.5). Downy brome was most susceptible to rimsulfuron and least susceptible to glyphosate (Figure 3.4).

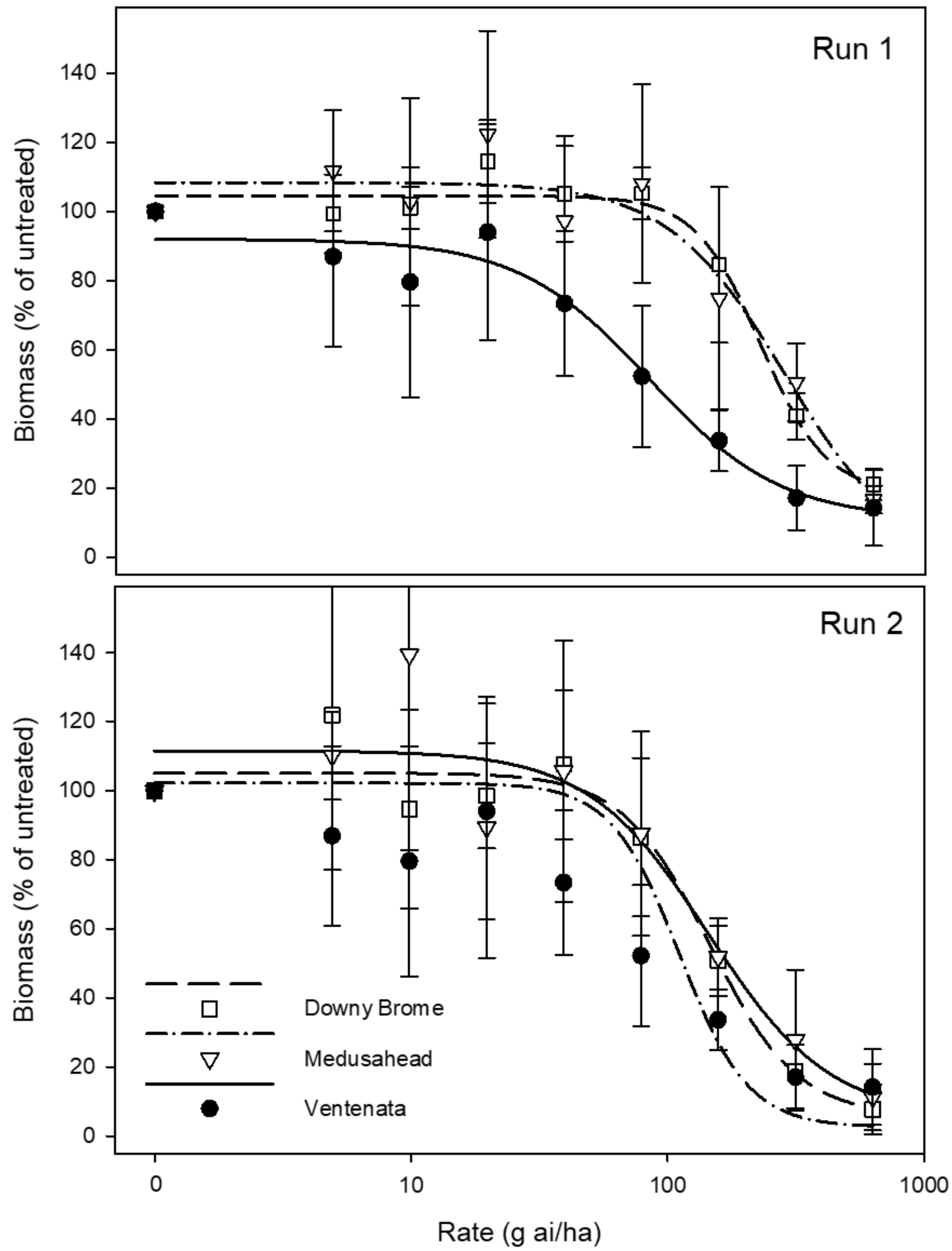

Figure 3.1. Response of three annual grasses to increasing glyphosate dosage in greenhouse trials. Runs 1 and 2 are illustrated separately.

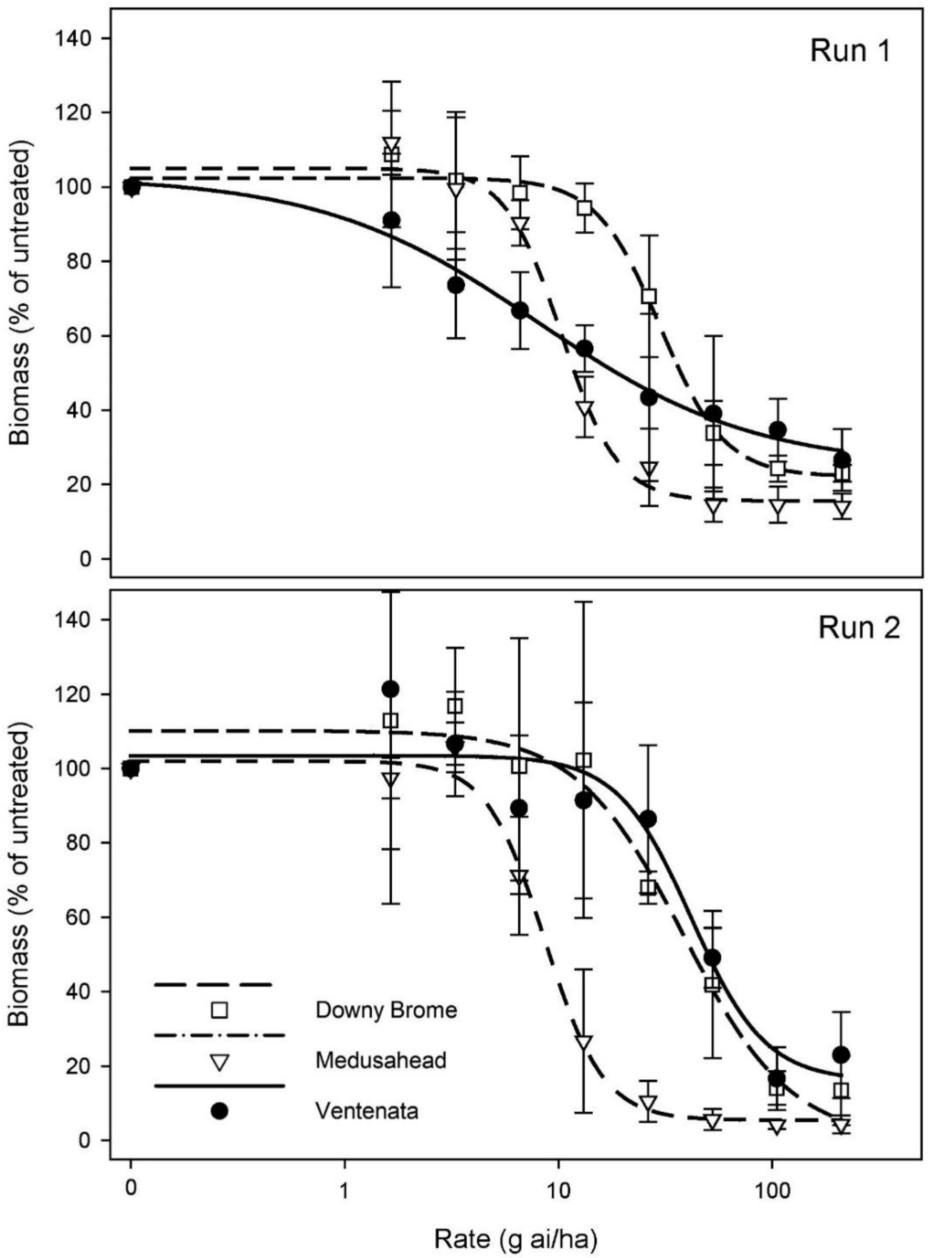

Figure 3.2. Response of three annual grasses to increasing imazapic dosage in greenhouse trials. Runs 1 and 2 are illustrated separately.

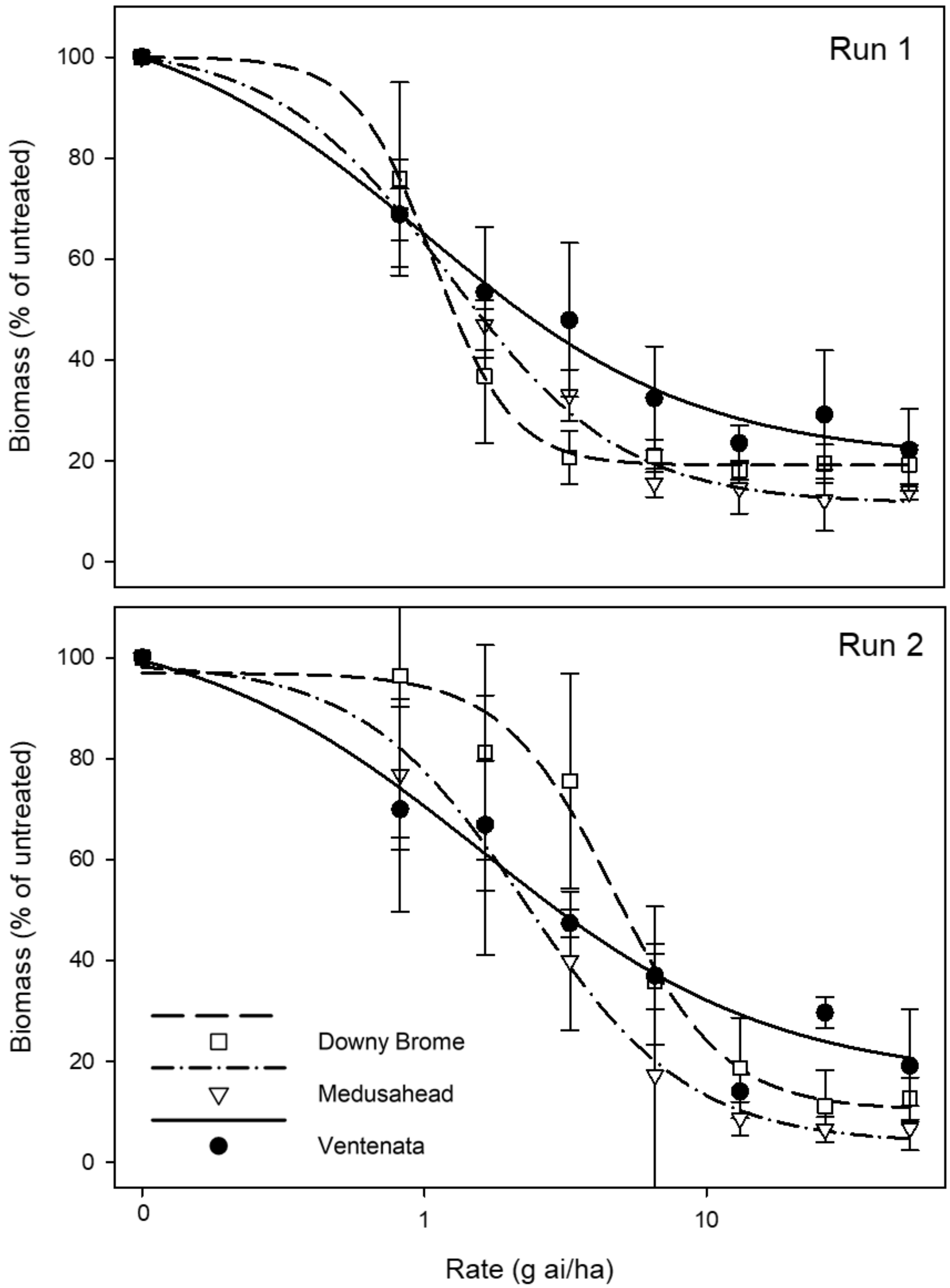

Figure 3.3. Response of three annual grasses to increasing rimsulfuron dosage in greenhouse trials. Runs 1 and 2 are illustrated separately.

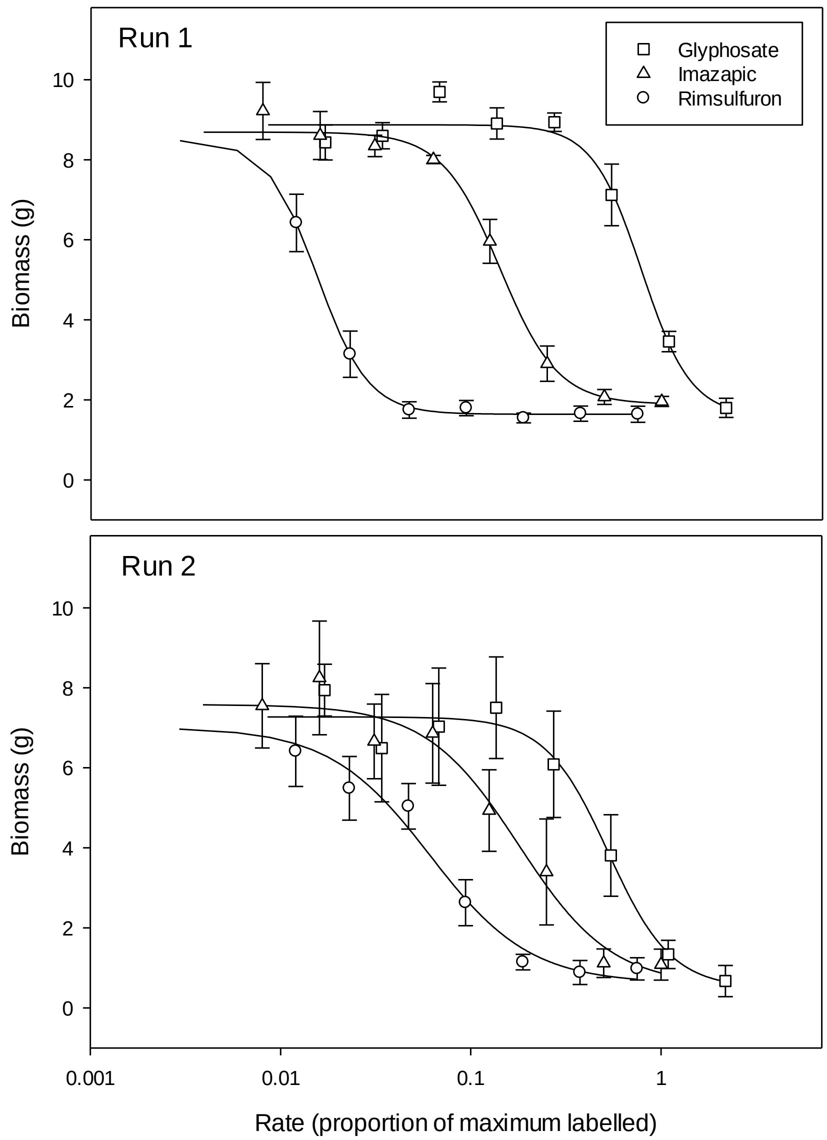

Figure 3.4. Regression of downy brome biomass in response to doses of three herbicides represented as a proportion of the maximum labelled rate in a rangeland setting. Runs 1 and 2 are illustrated separately.

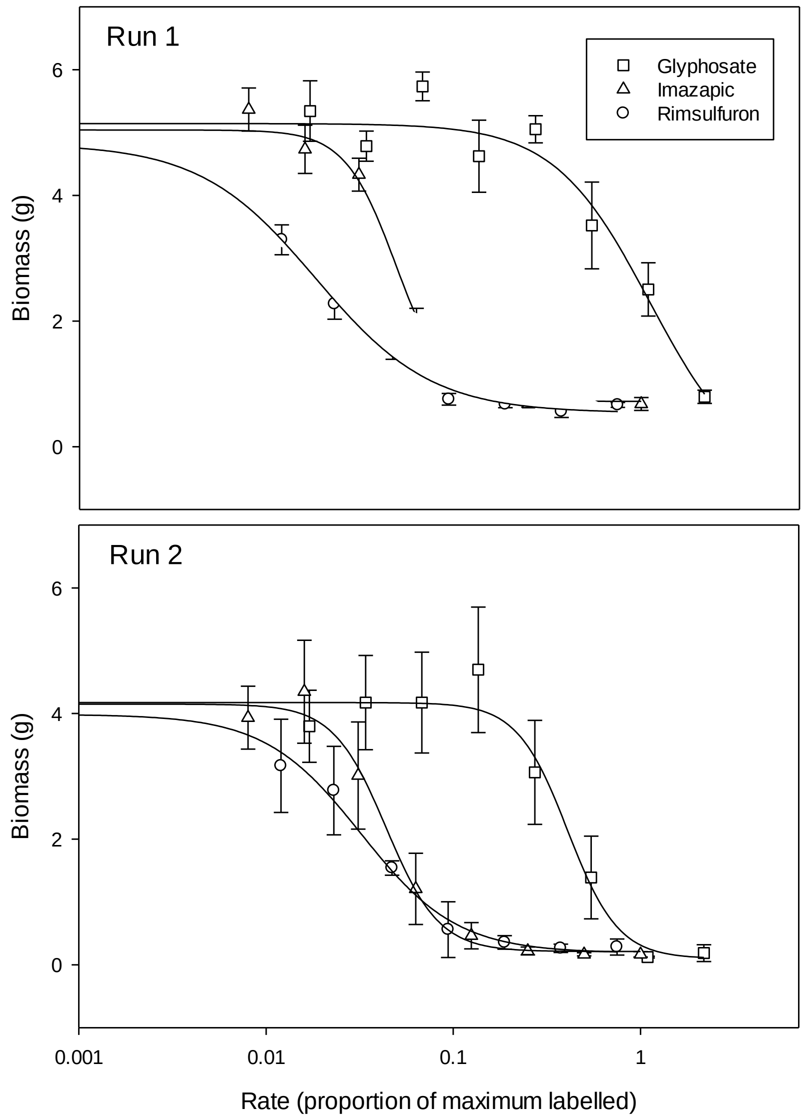

Figure 3.5. Regression of medusahead biomass in response to doses of three herbicides represented as a proportion of the maximum labelled rate in a rangeland setting. Runs 1 and 2 are illustrated separately.

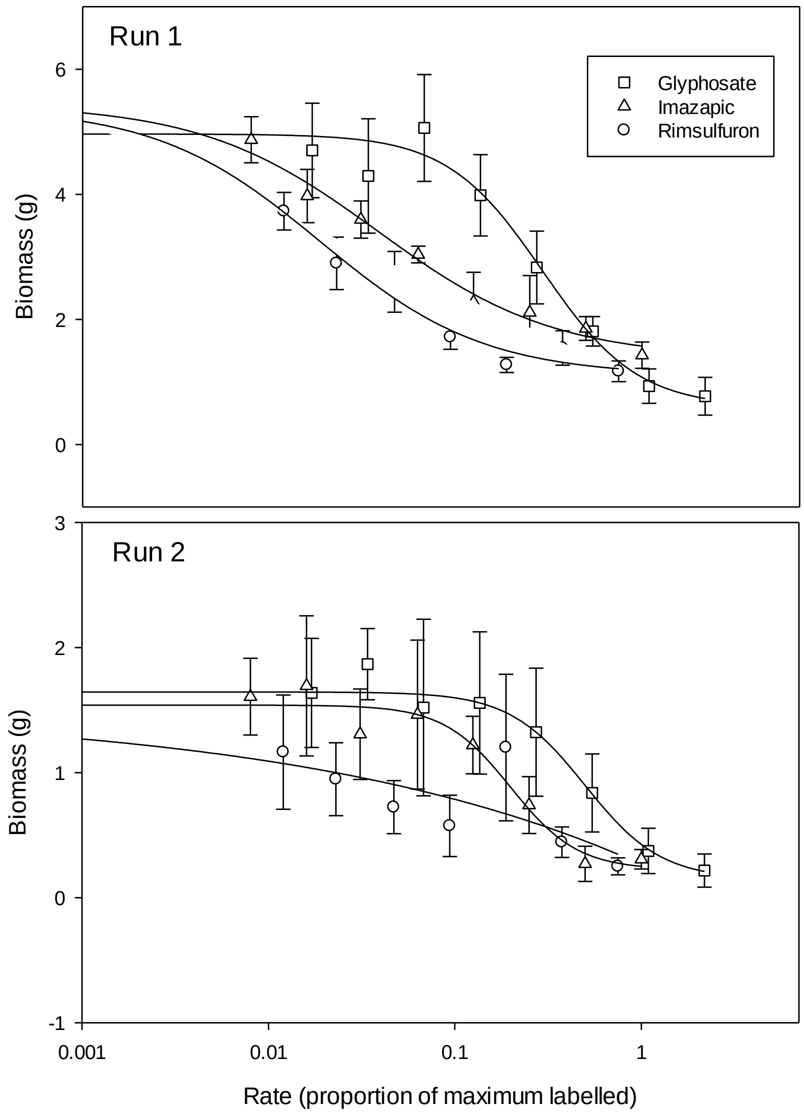

Figure 3.6. Regression of ventenata biomass in response to doses of three herbicides represented as a proportion of the maximum labelled rate in a rangeland setting. Runs 1 and 2 are illustrated separately.

In response to glyphosate, ventenata the EC_{50} value was significantly less compared to both medusahead ($p<0.01$) and downy brome ($p<0.01$) in the first run, whereas there were no differences in the second. In response to imazapic, downy brome EC_{50} value greater than for medusahead ($p<0.01$) and ventenata ($p=0.014$) in the first run and only higher than that of medusahead in the second run ($p<0.01$). In response to rimsulfuron, the only difference was that medusahead had a lower EC_{50} than downy brome in the second run ($p=0.023$).

When looking at downy brome, all herbicide EC_{50} values were significantly different in the first run with all p-values less than 0.01. In the second run, there were no differences for downy brome. In the first run, all herbicides were significant from one another when used on medusahead. In both runs, no herbicide EC_{50} value was different from another when used on ventenata. Glyphosate compared with imazapic and rimsulfuron both had p-values less than 0.01 and rimsulfuron and imazapic exhibited a p-value of 0.013. In the second run, the only differences were between glyphosate and imazapic ($p<0.01$) and glyphosate and rimsulfuron ($p=0.025$).

As well as providing the best overall control of all species, Rimsulfuron was also shown to work at the lowest doses in g/ha (Table 3.9) and the lowest proportion of the typical field rate (Table 3.10). Glyphosate was shown to have the highest EC_{50} values in terms of g/ha (Table 3.9) and proportion (Table 3.10), and imazapic was generally in between the two (Table 3.9, 3.10). This is not surprising given the overall differences in activity among these herbicides.

Table 3.9. Parameter estimates for 3-parameter dose-response curves describing herbicide by species (Equation 1).*

Herbicide	Species	EC 50 (x_0)				Max (a)				Slope (b)			
		Run 1		Run 2		Run 1		Run 2		Run 1		Run 2	
		g/ha											
Glyphosate	Downy Brome	281.10	(21.85)	164.26	(25.35)	8.93	(0.21)	7.31	(0.36)	1.23	(0.35)	2.23	(0.68)
	Medusahead	280.11	(43.26)	121.00	(32.17)	5.13	(0.22)	4.17	(0.40)	1.88	(0.48)	3.10	(1.71)
	Ventenata	102.72	(23.04)	165.56	(150.42)	5.09	(0.33)	1.66	(0.45)	1.23	(0.33)	1.76	(2.52)
Imazapic	Downy Brome	41.42	(3.72)	42.08	(7.79)	9.02	(0.23)	7.65	(0.42)	0.54	(0.15)	1.52	(0.38)
	Medusahead	12.38	(1.68)	9.71	(2.71)	5.22	(0.27)	4.17	(0.54)	1.73	(0.41)	2.70	(1.71)
	Ventenata	21.94	(7.56)	50.41	(49.76)	5.52	(0.36)	1.57	(0.47)	0.54	(0.09)	1.58	(2.50)
Rimsulfuron	Downy Brome	1.27	(0.24)	4.73	(0.93)	8.69	(0.38)	7.24	(0.49)	0.72	(0.12)	1.25	(0.27)
	Medusahead	1.53	(0.43)	2.40	(0.89)	4.87	(0.38)	4.03	(0.60)	0.88	(0.21)	1.46	(0.67)
	Ventenata	2.46	(0.94)	6.61	(16.33)	5.44	(0.38)	1.52	(0.61)	0.52	(0.11)	0.45	(0.53)

* Values are followed by standard errors in parentheses. Parameter estimates are based on dry aboveground biomass data.

Table 3.10. Parameter estimates for 3-parameter dose-response curves describing species in response to herbicide (Equation 1)* with EC 50 values expressed as proportions of maximum field rates.

		EC 50 (x_0) †		Max (a)		Slope (b)	
Species	Herbicide	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2
Ventenata	Glyphosate	0.36 (0.07)	0.57 (0.21)	5.10 (0.30)	1.66 (0.18)	1.23 (0.29)	1.75 (1.01)
	Imazapic	0.10 (0.04)	0.24 (0.10)	5.52 (0.40)	1.57 (0.20)	0.54 (0.10)	1.58 (1.06)
	Rimsulfuron	0.04 (0.01)	0.09 (0.13)	5.44 (0.41)	1.52 (0.35)	0.52 (0.12)	0.45 (0.30)
Medusahead	Glyphosate	0.97 (0.10)	0.42 (0.06)	5.13 (0.16)	4.17 (0.24)	1.89 (0.34)	3.09 (1.00)
	Imazapic	0.06 (0.01)	0.05 (0.01)	5.22 (0.24)	4.17 (0.33)	1.73 (0.35)	2.68 (1.05)
	Rimsulfuron	0.02 (0.01)	0.03 (0.01)	4.87 (0.32)	4.03 (0.50)	0.89 (0.18)	1.47 (0.55)
Downy Brome	Glyphosate	0.97 (0.08)	0.57 (0.11)	8.93 (0.21)	7.31 (0.46)	2.27 (0.36)	2.23 (0.87)
	Imazapic	0.20 (0.02)	0.20 (0.05)	9.02 (0.30)	7.65 (0.56)	1.35 (0.20)	1.52 (0.51)
	Rimsulfuron	0.02 (0.00)	0.02 (0.02)	8.68 (0.47)	7.24 (0.89)	0.72 (0.14)	1.25 (0.48)

* Values are followed by standard errors in parentheses. Parameter estimates are based on dry aboveground biomass data.

† EC 50 values are based on a proportion scale where the value 1 represents each herbicide at a maximum field application rate: Glyphosate at 288.8 g ai/ha = 1, Imazapic at 210 g ai/ha = 1, and Rimsulfuron at 70 g ai/ha = 1.

Discussion

Field Study. In this study, indaziflam was most effective for controlling ventenata at both 7 and 20 MAT compared to other herbicides. Only treatments including indaziflam provided consistent ventenata control from the untreated in all runs and evaluation times. A study conducted by Koby and colleagues (2019) using indaziflam in various combinations compared with rimsulfuron, imazapic, and glyphosate alone found that indaziflam alone and in combination provided more consistent control of ventenata at two locations than all other herbicides at 6 and 16 MAT (Koby *et al.* 2019). In both our study and the study conducted by Koby *et al.* (2019), rimsulfuron provided less consistent control but was also effective at earlier evaluation times. Glyphosate provided no significant control for any evaluation in both studies and Koby *et al.* (2019) explained that this may be due to a layer of thatch present at time of application acting as a barrier between the herbicide and the new seedlings. Another similar study presented by J. Beuschlein at the 2019 Western Society of Weed Science conference tested many of the same herbicides in combination with indaziflam on ventenata and other invasive annual grasses (Beuschlein *et al.* 2019). In this study, biomass was collected 21 months after treatment and indaziflam paired with rimsulfuron or imazapic reduced ventenata biomass by up to 97% (Beuschlein *et al.* 2019). Likewise, in our study, all indaziflam combinations reduced ventenata cover to zero or near zero for most evaluations. All these results indicate that indaziflam in combination with some herbicides provides consistent control of ventenata for more than one year.

Although ventenata was controlled with indaziflam when compared to the untreated plots in almost every instance, ventenata density increased between evaluations in 2018 and 2019. This may be due to the precipitation during the growing season. In early 2019, there was above average rainfall which may have been adequate to stimulate germination (Figure 3.7). In the second run, there was no such increase between evaluations. This could be attributed to the lack of rainfall during active germination, even though precipitation during the rest of the active growing season was largely above average (Figure 3.7). Similarly, this could explain why perennial grass cover decreased between evaluation times with most treatments in the first run but increased with most in the second. The excess rainfall in run 1 that allowed ventenata to surge likely allowed it to push out the perennial grasses. In run 2, when water was more scarce and ventenata cover was subsequently lower, the perennial grasses were able to fill the open canopy.

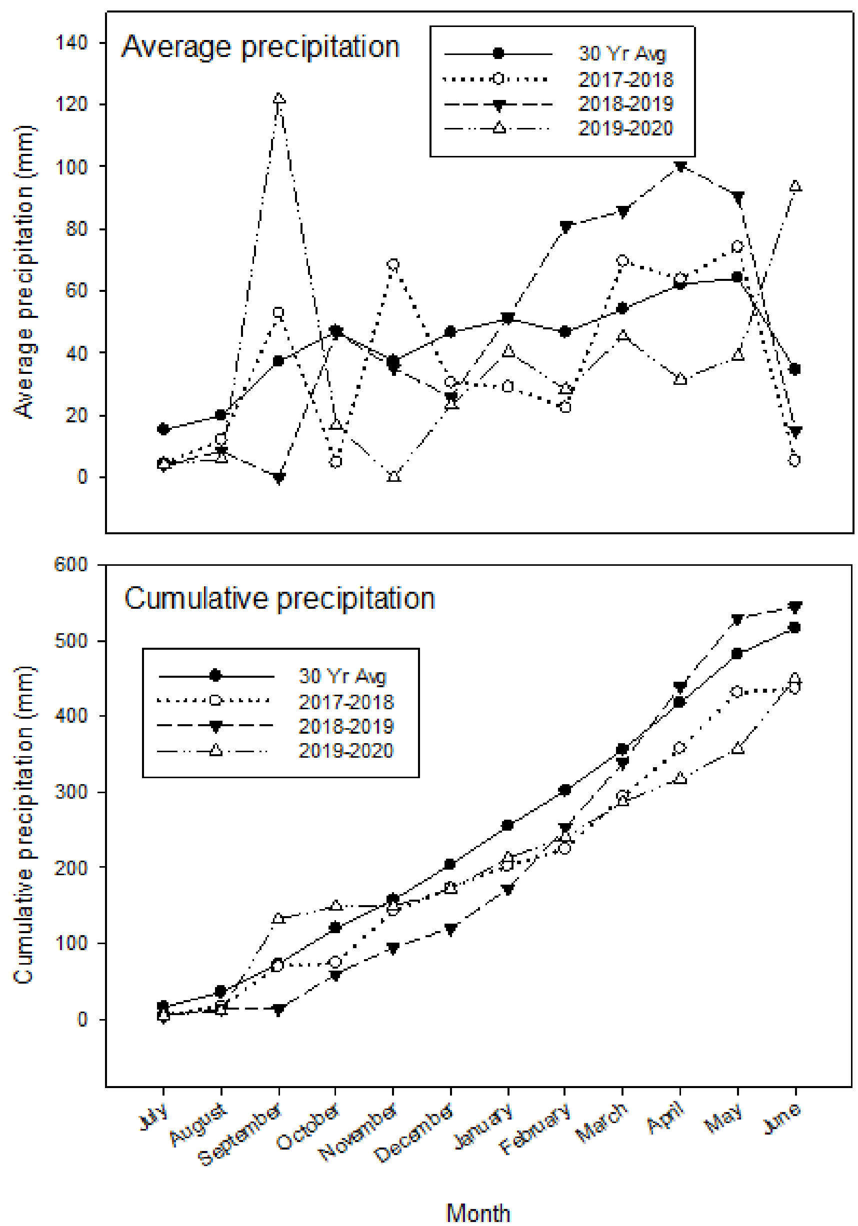

Figure 3.7. Average and cumulative precipitation during the duration of both runs of ventenata control trials.

Our results indicate that imazapic does not control ventenata in the second year after application; however, one study focusing on ventenata control with increasing imazapic rates observed consistent control for two years after treatment (Davies and Hamerlynck 2019). Another study observed nearly complete ventenata control with imazapic for one year at two different sites. By the second year, treatments were ineffective as ventenata cover was not different from the untreated plots (Koby *et al.* 2019). Control of ventenata with imazapic seems to be variable across sites and years based on current and previous research.

Effects of indaziflam and other herbicides on desirable perennial grasses on sites infested with ventenata seem to be variable across and within studies. In our study, perennial grasses generally decreased from one evaluation to the next in one run, and in the other, perennial grasses generally increased. Koby *et al.* (2019) observed little change in perennial grass cover from untreated plots for most evaluations but one, in which cover dramatically increased with all indaziflam combinations. The variability of perennial grasses in our study could be due to variability in biodiversity and weather. In the run where perennial grasses decreased, rainfall during active growth was below average and overall ventenata cover increased from 7 to 20 MAT, likely outcompeting the perennial grasses for moisture. This same conclusion was drawn by Koby and colleagues when explaining reductions in perennial grass biomass (Koby *et al.* 2019).

Herbicide treatment alone does not seem to have a strong impact on species richness. While richness was generally lower for indaziflam combination treatments in the second run, this reduction can be explained by much higher richness in untreated plots compared with the first run. In the second run, richness in plots treated with indaziflam in combination were numerically similar to corresponding plots in run one by 20 MAT. Species diversity seems to follow the same trend, with increases and reductions being inconsistent across evaluations, runs, and treatments.

Greenhouse Study. Contrary to what is generally observed in the field, in this study, ventenata exhibited more sensitivity to glyphosate than the other grasses (Beuschlein *et al.* 2019; Koby *et al.* 2019). Interestingly, our observed EC_{50} when using glyphosate on ventenata was 102.7 g ai/ha, whereas the EC_{50} values for the other two grasses were nearly triple, both at about 280 g ai/ha in Run 1. In run 2, the values for all grasses were more uniform. Our results with rimsulfuron line up well with trends observed in field studies, with higher rates controlling ventenata and other grasses to a high degree, and significant control also observed at lower rates (Wallace and Prather 2016, Beuschlein *et al.* 2019, Koby *et al.* 2019).

The EC_{50} values observed with imazapic (10-50 g ai/ha) are lower than field studies have previously indicated as well. One study conducted by Koby and colleagues (2019) found that ventenata density was reduced by 50% or more at rates of 70-105 g ai/ha. Another study observed a similar trend with 70 g ai/ha reducing ventenata density on average by 65% (Van Vleet 2011). This discrepancy could be due to the fact that greenhouse experiments are generally more controlled, or the fact that biomass and density are different measurements. To date, there are no published field studies observing the effects of imazapic on ventenata that measure dry biomass.

From what has been observed in field conditions including those in our own study, glyphosate alone has not had much of a notable effect on ventenata density (Beuschlein *et al.* 2019). Our results from the greenhouse trials do not match up with vententata control in the field. This implies that application timing is just as important as physiological response. In our study, all herbicides were applied when plants had already emerged, but we speculate that glyphosate is less effective in field settings because it is typically applied before many of the seedlings emerge. Imazapic, rimsulfuron, and indaziflam can all work well as preemergence herbicides, and imazapic and rimsulfuron can also act as postemergence herbicides, but glyphosate is only effective postemergence (Amrhein *et al.* 1980, Sebastian *et al.* 2016, Wallace and Prather 2016).

Our regression analyses are also consistent with what has been previously observed in field settings, including our concurrent field study, for rimsulfuron and imazapic. Previous work indicates that rimsulfuron alone is generally more effective at controlling invasive annual grasses at lower rates than imazapic, while imazapic is effective, but falls short of the near-complete control provided by rimsulfuron in many cases (Wallace and Prather 2016, Davies and Hammerlynck 2019). Notably, rimsulfuron acted more linearly on ventenata than the other grasses, with no clear inflection point in the curves for both runs. It was overall more sensitive at lower rates, but less sensitive at higher rates than the other grasses. Ventenata also exhibited a near-linear curve in response to imazapic in run 1 only. These linear responses may indicate that higher than typical rates may provide more consistent ventenata control in field settings. Also interesting to note is that medusahead was noticeably more sensitive to imazapic than the other two grasses. Medusahead response to imazapic varies greatly in the field (Monaco *et al.* 2005, Sheley *et al.* 2007, Kyser *et al.* 2013); however, a greenhouse study testing the effectiveness of imazapic and indaziflam on six invasive annual grasses including medusahead, downy brome, and ventenata found imazapic to be nearly equally effective on both medusahead and downy brome (GR_{50} ~2-3 g ai/ha), but less effective on ventenata (GR_{50} ~7 g ai/ha) (Sebastian *et al.* 2016). Collectively, these results indicate that while greenhouse studies may not always apply directly to field studies in terms of herbicide effectiveness, they are instrumental in determining individual plant responses in controlled environments. Information from this study and future studies will be useful for optimizing field treatments.

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CHAPTER IV

RESTORATION OF ONE MEDUSAHEAD INFESTED SITE IN UTAH USING A MULTIPLE-ENTRY APPROACH

Abstract

Medusahead (*Taeniatherum caput-medusae* (L.) Nevski) is an exotic winter annual grass native to the Mediterranean region of Eurasia and has invaded much of the western United States. Indaziflam is a relatively new preemergence herbicide that has been shown to prevent germination of annual grasses for at least three years following application. This project was designed to test the efficacy of herbicides alone and in combination with indaziflam on medusahead, and to compare revegetation efforts directly after herbicide application as well as one year after. Two runs of the trial were established on a site in Honeyville, Utah, one in 2017, and one in 2018. The trial was designed as a randomized strip-plot design with four replicates. Both strips for each treatment were sprayed at the same time with one strip being seeded with three grasses: Siberian wheatgrass, thickspike wheatgrass, and intermediate wheatgrass, and a broadleaf forb mix immediately following herbicide treatment, and the other being seeded one year after. The first planting in the first run failed; therefore, both strips were seeded the next year and the second run was seeded as originally planned. For every indaziflam treatment in both runs, all reseeded species remained unchanged from untreated plots except for one forb which increased for two of the treatments. Treatments including imazapic or aminopyralid were highly effective showing the most overall increase in reseeded species

compared with the untreated plots. This project provides insight and understanding required to revegetate highly degraded sites infested with medusahead monocultures.

Introduction

Medusahead is an invasive winter annual grass that has become a problem throughout much of the western United States (Young 1992). It is an aggressive competitor that decreases biodiversity, degrades rangelands and wildlife habitat, and contributes to increased fire frequency (Davies 2010; Sheley *et al.* 2012; Nafus and Davies 2014). The plant has an alarming spread rate of about 12% a year (Duncan *et al.* 2004; Nafus and Davies 2014). By 2014, an estimated 2.2 million hectares had been infested with medusahead in the western United States and another 25 million hectares are likely to be at risk of invasion (Nafus and Davies 2014). Medusahead can form monoculture or near-monoculture stands that are difficult to revegetate (Sheley *et al.* 2007; Sheley *et al.* 2012). The plant has a particularly high silica content, rendering it unpalatable as a forage plant, and allowing it to form a thick layer of thatch to suppress germination of its competitors while enhancing germination of its own seed (Monaco *et al.* 2005; Johnson and Davies 2012; Kyser *et al.* 2012).

Ridding a site of an invasive annual grass is only half the battle in rangeland restoration; there must be a stand of desirable plants to fill the open niche and keep the invasive annual grass from reinvading (Sheley *et al.* 2012; Kyser *et al.* 2013; Davies *et al.* 2015). In revegetation efforts, many naturalized, introduced grasses and forbs are used due to lower cost and generally better establishment and competitive ability compared to natives (Davies *et al.* 2015). Native seed is also a desirable option for revegetation of degraded sites because many introduced species can form monocultures, compete with native vegetation, and create lower quality habitat for wildlife (Pyke 1990; Gunnell *et al.* 2010; Davies *et al.* 2015). Herbicides are often used as the main method of control for annual grasses such as medusahead and downy brome, but these may negatively impact the seeds used for restoration depending on the chemical and timing of planting (Davies *et al.* 2014; Sebastian *et al.* 2016). Plants can be seeded the same year of herbicide application to rehabilitate lands (Single-entry approach), or seeds may be planted the year following application (Multiple-entry approach). Both methods can have positive and negative consequences, for example, the single-entry approach gives seeded species time to establish before invasive grasses reemerge and is more cost-effective, but the herbicides can affect the seeded vegetation as well as the invasive grasses (Davies *et al.* 2015; Clenet *et al.* 2019). Conversely, the multiple-entry approach can be more expensive and there is risk that the grasses might reinvade in the year before planting, but seeds may have a better chance of surviving and establishing due to the separation from the herbicide applications (Sheley *et al.* 2012; Davies *et al.* 2014; Clenet *et al.* 2019).

The pioneer studies implementing single- and multiple-entry approaches to manage and rehabilitate medusahead infested areas have primarily used imazapic and prescribed burns as methods of control before seeding (Davies 2010; Sheley *et al.* 2012; Davies *et al.* 2014; Davies *et al.* 2015; Davies and Boyd 2018). These treatments are often effective for only one year after application as imazapic is comparatively immobile in soil and has a moderate adsorption capacity (Davies 2010; Su *et al.* 2019). Indaziflam is a relatively new cellulose biosynthesis inhibiting herbicide that has been shown to have at least three years of soil residual activity (Clark *et al.* 2019). It has not yet been extensively tested for managing invasive annual grasses; therefore, little is known about how it affects desirable vegetation (Sebastian *et al.* 2016; Clark *et al.* 2019). Only one published study to date has tested its efficacy with simultaneous revegetation. Clenet and colleagues (2019) conducted a study in a grow room at the Eastern Oregon Agricultural Research Center using indaziflam to manage medusahead while concurrently planting seeds encased in activated carbon pods. However, no studies have yet tested indaziflam in a multiple-entry revegetation approach, likewise no other studies have tested indaziflam in combination with different herbicides to manage invasive annual grasses in a field setting (Sebastian *et al.* 2017; Clenet *et al.* 2019). The purpose of this research was to compare both the single-entry and multiple-entry approaches on a heavy stand of medusahead using a variety of herbicides alone and in combination with indaziflam. Revegetated species were bare-seeded and both native and introduced.

Materials and Methods

A site was chosen at a degraded foothill in Honeyville, Utah (41°39’47” N, 112°04’32” W; 1400 m elevation) because of the near-monoculture stand of medusahead present and the potential for revegetation and restoration of the site. The experiment was originally organized as a randomized strip-plot design replicated four times with two runs established on the same site in 2017 and 2018, respectively. The first strip of each replicate was re-seeded the same year of herbicide application and the second strip was re-seeded one year after application. Individual plots measured 3 meters by 9 meters. Herbicide treatments were applied to both strips of each replicate immediately after runs were established in 2017 and 2018. Because there was no emergence from the 2017 planting in the first run, both strips of run 1 were seeded simultaneously with the first strip of run 2 in 2018. Run 2 was seeded as originally planned, with the first strip seeded in 2018 and the second in 2019.

An overgrowth of sunflower required an additional herbicide, clopyralid, which was applied to only one half of every plot in both strips of each replicate for the first run, and only the first strip of each replicate for the second run (figure 4.1, figure 4.2). There was not enough difference in plot halves treated with clopyralid to warrant separate data analysis from those not treated, so data from halves treated with clopyralid and not treated with clopyralid were combined.

2018 planting:

Buffer →
Broadleaf mix →
Intermediate wheatgrass →
Thickspike wheatgrass →
Siberian wheatgrass →
Untreated →

111	112	113	114	115	116	117	118	119	120
Untreated	Imazapic 79 g ai/ha	Imazapic 105 g ai/ha	Imazapic 131 g ai/ha	Indaziflam 44 g ai/ha Glyphosate 532 g ai/ha	Indaziflam 73 g ai/ha Glyphosate 532 g ai/ha	Indaziflam 102 g ai/ha Glyphosate 532 g ai/ha	Aminopyralid 184 g ai/ha Glyphosate 532 g ai/ha	Aminopyralid 184 g ai/ha Glyphosate 532 g ai/ha	Glyphosate 532 g ai/ha
	**	**	**	**	**	**	**	* **	**

2018 planting:

Buffer →
Broadleaf mix →
Intermediate wheatgrass →
Thickspike wheatgrass →
Siberian wheatgrass →
Untreated →

101	102	103	104	105	106	107	108	109	110
Untreated	Imazapic 79 g ai/ha	Imazapic 105 g ai/ha	Imazapic 131 g ai/ha	Indaziflam 44 g ai/ha Glyphosate 532 g ai/ha	Indaziflam 73 g ai/ha Glyphosate 532 g ai/ha	Indaziflam 102 g ai/ha Glyphosate 532 g ai/ha	Aminopyralid 184 g ai/ha Glyphosate 532 g ai/ha	Aminopyralid 184 g ai/ha Glyphosate 532 g ai/ha	Glyphosate 532 g ai/ha
	**	**	**	**	**	**	**	* **	**

Glyphosate at 532 g ai/ha applied in winter 2018 (plots 102–110)

* Indaziflam at 73 g ai/ha applied summer after treatment
** Clopyralid applied spring 2019 to one half of each plot

Figure 4.1. Plot and treatment map of run 1 established in 2017.

2019 planting:

Buffer →
Broadleaf mix →
Intermediate wheatgrass →
Thickspike wheatgrass →
Siberian wheatgrass →
Untreated →

111	112	113	114	115	116	117	118	119	120
Untreated	Imazapic 79 g ai/ha	Imazapic 105 g ai/ha	Imazapic 131 g ai/ha	Indaziflam 44 g ai/ha Glyphosate 532 g ai/ha	Indaziflam 73 g ai/ha Glyphosate 532 g ai/ha	Indaziflam 102 g ai/ha Glyphosate 532 g ai/ha	Aminopyralid 184 g ai/ha Glyphosate 532 g ai/ha	Aminopyralid 184 g ai/ha Glyphosate 532 g ai/ha	Glyphosate 532 g ai/ha
								*	

2018 planting:

Buffer →
Broadleaf mix →
Intermediate wheatgrass →
Thickspike wheatgrass →
Siberian wheatgrass →
Untreated →

101	102	103	104	105	106	107	108	109	110
Untreated	Imazapic 79 g ai/ha	Imazapic 105 g ai/ha	Imazapic 131 g ai/ha	Indaziflam 44 g ai/ha Glyphosate 532 g ai/ha	Indaziflam 73 g ai/ha Glyphosate 532 g ai/ha	Indaziflam 102 g ai/ha Glyphosate 532 g ai/ha	Aminopyralid 184 g ai/ha Glyphosate 532 g ai/ha	Aminopyralid 184 g ai/ha Glyphosate 532 g ai/ha	Glyphosate 532 g ai/ha
								*	
	**	**	**	**	**	**	**	**	**

* Indaziflam at 73 g ai/ha applied summer after treatment
** Clopyralid applied spring 2019 to one half of each plot

Figure 4.2. Plot and treatment map of run 2 established in 2018.

Original herbicide treatments included: imazapic at 79 g ai/ha, imazapic at 105 g ai/ha, imazapic at 131 g ai/ha, indaziflam at 44 g ai/ha with glyphosate at 532 g ai/ha, indaziflam at 73 g ai/ha with glyphosate at 532 g ai/ha, indaziflam at 102 g ai/ha with glyphosate at 532 g ai/ha, aminopyralid at 184 g ai/ha with glyphosate at 532 g ai/ha, aminopyralid at 184 g ai/ha with glyphosate at 532 g ai/ha plus indaziflam applied the following summer at 44 g ai/ha, and glyphosate at 532 g ai/ha. All treatments were applied in the fall of establishment with a CO_2-pressurized backpack sprayer calibrated to deliver 234 L/ha at 276 kPa and all treatments included a non-ionic surfactant at 0.25% v/v. Each herbicide treatment was applied once in both the first and second strips of each replicate for each run.

Re-seeding treatments included “Vavilov” Siberian wheatgrass (*Agropyron fragile*), “Bannock” thickspike wheatgrass (*Elymus lanceolatus*), “Rush” intermediate wheatgrass (*Agropyron intermedia*), and a broadleaf mix consisting of alfalfa (*Medicago sativa*), blue flax (*Linum lewisii*), small burnet (*Sanguisorba minor*), forage kochia (*Kochia prostrata*), and western yarrow (*Achillea millefolium*). Seeds were planted using a Trueax no-till drill (Trueax FLEXII-88, New Hope MN) in passes 1.5 meters wide across each strip with 0.15 meters in between each row and a buffer of 0.75 meters at the end of each strip. Seeded plants failed to emerge after the first planting in the first run due to low moisture; therefore, both strips were re-seeded the following year and the second strip was sprayed with glyphosate at 578 g ai/ha during the winter of 2018 before planting (Figure 4.1). The second run was seeded as planned with the second strip receiving a treatment of glyphosate at 578 g ai/ha in the winter of 2019 to match the first run (Figure 4.2).

Plots were evaluated visually for percent control of medusahead in the spring for two years following treatment. After successful germination from plantings, seedling emergence was evaluated the summer after planting using quadrats in one half of each plot for each species. Quadrats measured 1 m by 0.5 m. All data were analyzed using general linear model or repeated measure ANOVA.

Results

Of the planted species, all grasses were present for both runs and small burnet and flax were recorded at relatively high rates. Alfalfa was present and recorded at trace amounts in some plots, but the counts were not significant for most treatments and are not included in results tables. Yarrow and forage kochia were not recorded after planting.

All re-seeded species treated with indaziflam in the fall for all evaluation times and years remained unchanged from their respective untreated plots except for small burnet, which increased from the untreated at some rates and evaluation times (Table 4.2, 4.4). Untreated plots and fall indaziflam treated plots yielded among the lowest means for all re-seeded species. Overall, plots not sprayed with glyphosate in the winter following initial treatments in run 1 were not different from untreated plots (Table 4.1, 4.2). Of the plots in run 2 not treated with glyphosate in the winter, plant counts of those treated initially with imazapic generally increased from untreated plots (Table 4.3, 4.4). For both runs, aminopyralid treatments without subsequent glyphosate application yielded among the highest means observed for most plants at most evaluation times (Table 4.1, 4.2, 4.3, 4.4). In run 1, plots treated with glyphosate prior to seeding in 2018 exhibited plant counts numerically higher than all other plots, especially those of Siberian wheatgrass (Table 4.1). This trend was not observed in run 2, where counts were generally low overall. Various plots treated with glyphosate alone observed an increase in some re-seeded plants at the first evaluation, but counts were reduced to among the lowest means by the second evaluation time (Table 4.3, 4.4). Plots treated with imazapic or aminopyralid yielded the most overall increase of revegetated species.

Table 4.1. Re-seeded grass species densities in response to herbicide treatments over time. Run 1 established in 2017.

Treatment*	Rate	Density					
		Intermediate wheatgrass†		Thickspike wheatgrass†		Siberian wheatgrass†	
		22 MAT	32 MAT	22 MAT	32 MAT	22 MAT	32 MAT
	g ai/ha	plants/m^2					
Untreated	-	3.25 k-n	0.00 n	0.50 n	0.00 j	1.00 j	0.00 j
Imazapic‡	79	17.00 d-g	14.50 e-i	21.25 e-i	9.75 d-h	38.00 efg	51.75 cde
Imazapic‡	105	22.25 cde	10.50 g-k	19.00 g-k	8.00 d-j	51.25 cde	49.50 cde
Imazapic‡	131	27.00 bc	16.25 d-h	21.25 d-h	16.25 bcd	65.00 bc	98.50 a
Indaziflam‡§	44	2.75 k-n	3.75 k-n	1.00 k-n	1.75 g-j	4.50 j	4.00 j
Indaziflam‡§	73	0.25 n	0.25 n	1.50 n	0.00 j	2.25 j	0.50 j
Indaziflam‡§	102	0.25 n	0.00 n	0.00 n	0.00 j	0.00 j	0.25 j
Aminopyralid‡§	184	37.75 a	31.50 ab	35.25 ab	9.25 d-i	55.25 cd	74.25 b
Aminopyralid‡§‖	184	24.75 bcd	21.75 cde	21.50 cde	12.00 cde	43.25 def	44.50 def
Glyphosate‡	532	19.25 c-f	10.25 g-l	13.00 g-l	10.25 c-g	26.50 gh	32.25 fg
Untreated	-	2.25 k-n	0.50 mn	1.25 mn	0.00 j	8.50 ij	8.25 ij
Imazapic	79	1.75 lmn	1.00 mn	0.25 mn	0.25 ij	0.00 j	1.75 j
Imazapic	105	5.75 j-n	0.75 mn	3.25 mn	2.75 f-j	0.50 j	1.00 j
Imazapic	131	6.75 i-n	3.25 k-n	0.75 k-n	0.25 ij	4.50 j	3.00 j
Indaziflam§	44	4.00 j-n	9.00 g-m	0.00 g-m	2.25 f-j	1.25 j	2.50 j
Indaziflam§	73	0.50 mn	0.50 mn	0.00 mn	0.00 j	0.50 j	1.25 j
Indaziflam§	102	0.00 n	2.50 k-n	0.50 k-n	1.00 hij	0.50 j	0.75 j
Aminopyralid§	184	7.75 h-n	3.00 k-n	3.25 k-n	11.00 c-f	6.50 ij	10.00 hij
Aminopyralid§‖	184	0.00 n	0.50 mn	0.00 mn	0.00 j	0.00 j	0.00 j
Glyphosate	532	12.50 f-j	1.25 mn	2.50 mn	7.50 d-j	22.50 ghi	9.00 ij

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

† Values labeled with the same letter within the two columns under each heading are not significantly different according to Fisher's protected LSD at p=0.05.

‡ Glyphosate at 532 g ai/ha was sprayed in winter of 2018 in addition to original treatments

§ Glyphosate at 532 g ai/ha was sprayed concurrently with above treatments

‖ Indaziflam at 73 g ai/ha was sprayed in the summer of 2018

Table 4.2. Re-seeded broadleaf species densities in response to herbicide treatments over time. Run 1 established in 2017.

Treatment[*]	Rate	Density											
		Small Burnet[†]				Flax[†]				Total Broadleaf[†]			
		22 MAT		32 MAT		22 MAT		32 MAT		22 MAT		32 MAT	
	g ai/ha	plants/m^2											
Untreated	-	3.25	k-p	2.50	m-p	3.50	c	0.25	c	6.75	e-j	2.75	hij
Imazapic[‡]	79	15.50	abc	9.25	d-i	9.00	ab	2.50	c	25.50	a	13.00	b-e
Imazapic[‡]	105	14.75	bc	11.00	c-g	10.25	ab	0.75	c	26.00	a	13.00	b-e
Imazapic[‡]	131	16.25	ab	8.75	d-j	12.50	a	0.75	c	29.50	a	10.25	c-g
Indaziflam[‡§]	44	11.25	c-f	9.75	d-h	3.75	c	2.25	c	15.00	bcd	12.25	b-f
Indaziflam[‡§]	73	4.25	j-p	6.25	g-n	0.25	c	0.00	c	5.25	g-j	6.25	e-j
Indaziflam[‡§]	102	4.00	j-p	3.00	l-p	0.00	c	0.00	c	4.75	g-j	3.00	hij
Aminopyralid[‡§]	184	19.75	a	14.75	bc	10.00	ab	2.75	c	30.25	a	17.50	b
Aminopyralid[‡§‖]	184	17.25	ab	13.25	bcd	8.00	b	2.25	c	26.50	a	16.50	bc
Glyphosate[‡]	532	16.25	ab	12.75	b-e	10.75	ab	3.00	c	27.50	a	16.00	bc
Untreated	-	4.25	j-p	5.00	h-o	1.75	c	0.00	c	6.00	f-j	5.00	g-j
Imazapic	79	7.00	f-m	5.25	h-o	1.50	c	0.50	c	8.50	d-i	5.75	f-j
Imazapic	105	0.50	op	1.75	nop	1.75	c	0.00	c	2.50	hij	2.00	ij
Imazapic	131	2.50	m-p	1.75	nop	1.50	c	0.25	c	4.25	g-j	2.25	hij
Indaziflam[§]	44	8.00	e-k	8.75	d-j	0.25	c	0.00	c	8.25	d-i	9.00	d-h
Indaziflam[§]	73	5.50	h-n	6.00	h-n	0.00	c	0.00	c	5.50	f-j	6.00	f-j
Indaziflam[§]	102	1.75	nop	4.75	i-p	0.00	c	0.00	c	2.00	ij	4.75	g-j
Aminopyralid[§]	184	4.00	j-p	7.75	f-l	0.25	c	0.50	c	4.50	g-j	8.25	d-i
Aminopyralid[§‖]	184	0.00	p	0.00	p	0.00	c	0.00	c	0.00	j	0.00	j
Glyphosate	532	2.50	m-p	1.75	nop	1.00	c	0.00	c	4.75	g-j	2.50	hij

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

[†] Values labeled with the same letter within the two columns under each heading are not significantly different according to Fisher's protected LSD at p=0.05.

[‡] Glyphosate at 532 g ai/ha was sprayed in winter of 2018 in addition to original treatments

[§] Glyphosate at 532 g ai/ha was sprayed concurrently with above treatments

[‖] Indaziflam at 73 g ai/ha was sprayed in the summer of 2018

Table 4.3. Re-seeded grass species densities in response to herbicide treatments over time. Run 2 established in 2018.

Treatment[*]	Rate	Density: Intermediate Wheatgrass[†] 22 MAT	Intermediate Wheatgrass[†] 32 MAT	Thickspike Wheatgrass[†] 22 MAT	Thickspike Wheatgrass[†] 32 MAT	Siberian Wheatgrass[†] 22 MAT	Siberian Wheatgrass[†] 32 MAT
	g ai/ha	plants/m^2					
Untreated	-	1.00 fgh	0.25 gh	2.75 de	0.00 e	0.50 fg	0.50 fg
Imazapic	79	6.00 bcd	9.25 ab	1.00 e	1.75 e	4.25 c-g	3.50 d-g
Imazapic	105	5.00 cde	3.50 d-g	4.00 b-e	3.00 de	6.50 cde	2.50 efg
Imazapic	131	10.00 a	9.00 ab	3.50 cde	2.00 e	4.75 c-f	12.25 ab
Indaziflam[‡]	44	0.00 h	0.00 h	0.00 e	0.00 e	0.25 g	0.00 g
Indaziflam[‡]	73	0.00 h	0.00 h	0.25 e	0.00 e	0.00 g	0.00 g
Indaziflam[‡]	102	0.25 gh	0.00 h	0.00 e	0.75 e	0.00 g	0.00 g
Aminopyralid[‡]	184	3.75 def	2.50 e-h	7.50 bcd	14.50 a	8.50 bc	12.00 ab
Aminopyralid[‡ǀ]	184	5.50 cde	4.25 def	9.00 b	8.50 bc	4.75 c-f	14.25 a
Glyphosate	532	8.00 abc	3.75 def	1.50 e	0.50 e	4.00 d-g	7.00 cd
Untreated	-		0.00 d		0.00 d		1.25 b
Imazapic	79		4.75 abc		3.00 abc		10.25 ab
Imazapic	105		8.50 a		5.00 a		27.25 a
Imazapic	131		3.50 bcd		5.50 a		15.75 ab
Indaziflam[‡]	44		2.00 bcd		0.00 d		4.25 b
Indaziflam[‡]	73		0.50 d		0.00 d		0.50 b
Indaziflam[‡]	102		0.50 d		0.00 d		0.50 b
Aminopyralid[‡]	184		5.50 ab		2.25 bcd		4.00 b
Aminopyralid[‡§]	184		1.00 cd		0.75 cd		5.25 b
Glyphosate	532		2.75 bcd		3.50 ab		3.25 b

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

[†] Values labeled with the same letter within the two columns under each heading for the first ten treatments are not significantly different according to Fisher's protected LSD at p=0.05. Values labeled with the same letter under each heading at 32 MAT for the second ten treatments are likewise not significantly different.

[‡] Glyphosate at 532 g ai/ha was sprayed concurrently with above treatments

[§] Indaziflam at 73 g ai/ha was sprayed in the summer of 2019

Table 4.4. Re-seeded broadleaf species densities in response to herbicide treatments over time. Run 2 established in 2018.

Treatment[*]	Rate	Density											
		Small Burnet[†]				Flax[†]				Total Broadleaf[†]			
		22 MAT		32 MAT		22 MAT		32 MAT		22 MAT		32 MAT	
	g ai/ha	plants/m^2											
Untreated	-	1.25	ghi	1.25	ghi	1.00	b	0.25	b	2.25	de	1.50	ef
Imazapic	79	1.00	hij	2.75	cde	0.25	b	0.50	b	2.00	de	3.25	cd
Imazapic	105	0.50	ijk	2.25	def	0.25	b	0.25	b	1.25	ef	3.25	cd
Imazapic	131	0.50	ijk	2.00	efg	0.00	b	0.00	b	1.50	ef	2.50	de
Indaziflam[‡]	44	0.00	k	0.00	k	0.00	b	0.00	b	0.00	f	0.00	f
Indaziflam[‡]	73	0.00	k	0.25	jk	0.00	b	0.00	b	0.00	f	0.25	f
Indaziflam[‡]	102	0.00	k	0.00	k	0.00	b	0.00	b	0.00	f	0.00	f
Aminopyralid[‡]	184	1.75	fgh	4.00	b	0.75	b	2.50	a	2.50	de	6.50	a
Aminopyralid[‡ǁ]	184	2.50	def	5.75	a	0.75	b	1.00	b	3.25	cd	6.75	a
Glyphosate	532	3.00	cd	3.50	bc	2.75	a	0.75	b	6.00	ab	4.75	bc
Untreated	-			0.00	d			0.75	c			0.75	b
Imazapic	79			5.00	a			3.75	a			8.75	a
Imazapic	105			4.50	ab			3.00	ab			7.50	a
Imazapic	131			5.50	a			3.75	a			9.25	a
Indaziflam[‡]	44			2.25	bcd			0.75	c			3.00	b
Indaziflam[‡]	73			2.50	bc			0.25	c			2.75	b
Indaziflam[‡]	102			1.25	cd			0.25	c			1.50	b
Aminopyralid[‡]	184			1.75	cd			1.50	bc			3.25	b
Aminopyralid[‡§]	184			0.25	cd			1.25	bc			1.50	b
Glyphosate	532			2.00	cd			1.00	bc			3.25	b

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

[†] Values labeled with the same letter within the two columns under each heading for the first ten treatments are not significantly different according to Fisher's protected LSD at p=0.05. Values labeled with the same letter under each heading at 32 MAT for the second ten treatments are likewise not significantly different.

[‡] Glyphosate at 532 g ai/ha was sprayed concurrently with above treatments

[§] Indaziflam at 73 g ai/ha was sprayed in the summer of 2019

Discussion

The results from this study demonstrate that when revegetating a site degraded by medusahead, a multiple-entry approach is more effective than a single-entry approach. Re-seeded plants established at a relatively high rate in plots where multiple herbicides were sprayed one year before planting. Many factors can hinder the site restoration, such as moisture and weather. The study was unable to be carried out as originally planned due to a failed first planting. This likely resulted from below average cumulative precipitation from 2017-2018, and especially low moisture during the early months of 2018 when the seeds would have normally germinated (Figure 4.3). Drought can also affect site restoration and plant establishment. The second strip of run 2 was seeded before a drought in the beginning of 2020; thus, germination numbers were relatively low. Likewise, plant counts generally declined in run 1 between 22 and 32 MAT (2019-2020), where precipitation was below average almost every month (Figure 4.3).

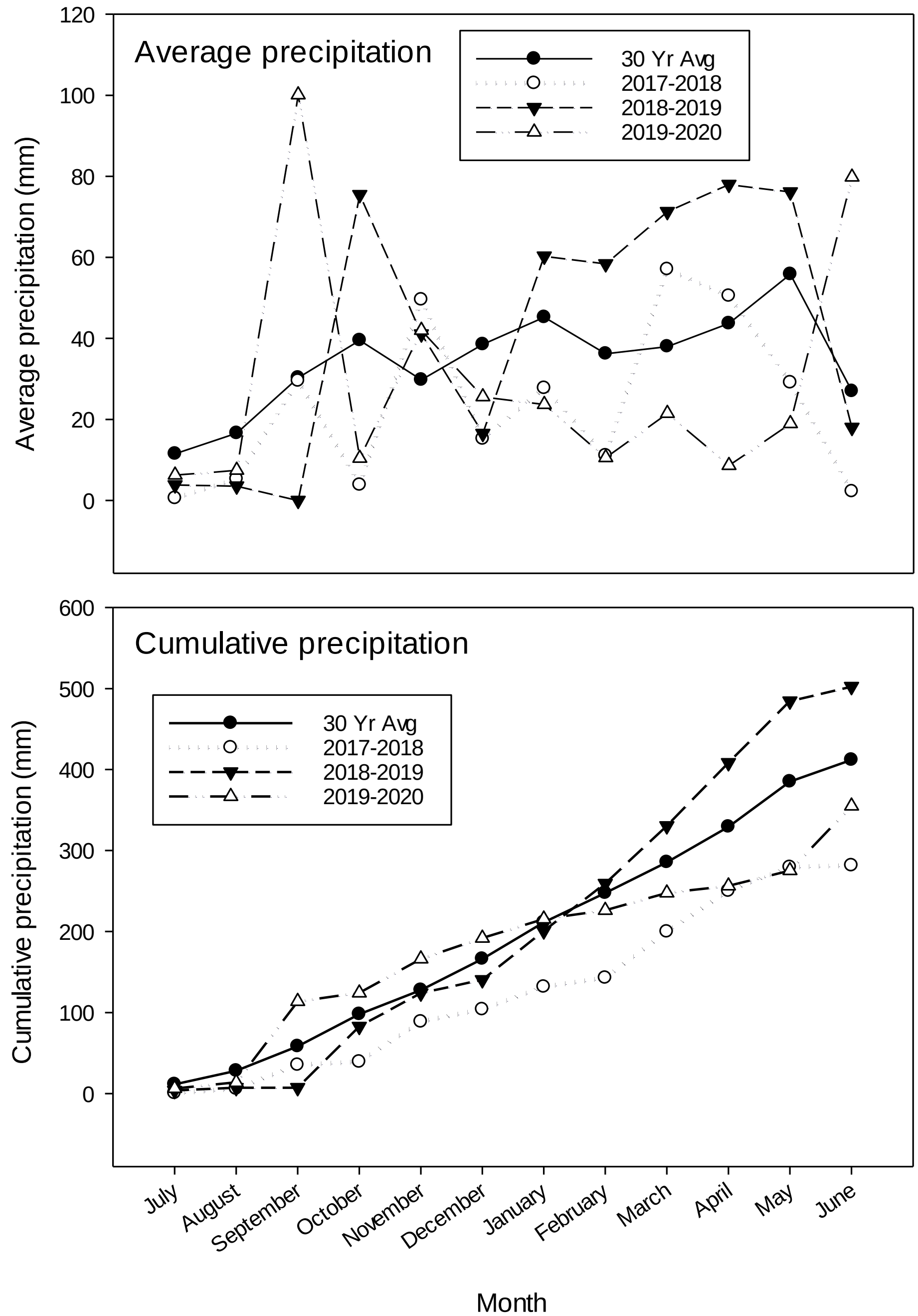

Figure 4.3. Average and cumulative precipitation during reseeding trials.

Stonecipher and colleagues conducted a similar study to ours in eastern Washington on a site infested with medusahead re-seeding with two of the same grasses from our study: Siberian wheatgrass and thickspike wheatgrass (2016). All plots were sprayed with glyphosate to rid the plots of other vegetation before planting (Stonecipher *et al.* 2016). The overall results from our run 1 support the methods used by Stonecipher *et al.* in that the plots sprayed with glyphosate in the winter following initial treatment allowed for better establishment due to less competition from other vegetation (2016).

A study by Davies and colleagues found success in revegetating medusahead infested rangeland by using imazapic in a multiple-entry approach as opposed to single-entry (2014). Their methods included herbicide application and prescribed burn, while ours paralleled with initial herbicide application followed by glyphosate in winter. Because our first seeding failed, both strips of run 1 were seeded one year after herbicide application. Both studies resulted in greater establishment of seeded species under favorable environmental conditions (Davies *et al.* 2014). Treatments including imazapic or aminopyralid in our study allowed for consistent successful establishment of all seeded species, especially broadleaves and Siberian wheatgrass. The highest establishment was observed in multiple-entry plots initially treated with imazapic or aminopyralid followed by glyphosate before seeding.

This study indicates that indaziflam is not useful for restoration of highly degraded sites if attempting to revegetate. As a cellulose-biosynthesis inhibitor, indaziflam prevented germination of most seeded species. The only species in this study that consistently established in plots treated with indaziflam was small burnet.

Results from this study suggest that revegetation is difficult under low-moisture conditions and that weather may be even more critical for site restoration than herbicide combination. Herbicides may allow for establishment of species on highly degraded sites, but moisture dictates long-term persistence of revegetated species. This study also suggests that it is difficult to establish desirable vegetation into indaziflam even one year after application. A multiple-entry approach with use of more than one herbicide not including indaziflam yielded desirable results. Future research should evaluate soil moisture throughout the study to see if multiple entry approaches result in higher soil moisture content compared to treatments with only a single year of medusahead suppression.

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CHAPTER V

SUMMARY AND CONCLUSIONS

Invasive annual grasses are a serious concern on rangelands in the Great Basin area (Monaco *et al.* 2005; Clark *et al.* 2019). Three of these grasses: downy brome, medusahead, and ventenata, significantly threaten biodiversity, soil health, and wildlife habitat (Wallace and Prather 2016; Davies and Hamerlynck 2019). Indaziflam is a relatively new preemergence herbicide that has a long period of soil residual activity and has been shown to prevent germination of annual grasses for at least three years (Sebastian *et al.* 2017).

Downy brome has become one of the most invasive weeds in North America to date and has infested several million hectares of land since its introduction in the mid-nineteenth century (Morrow and Stahlman 1984; Clark *et al.* 2019). A site near Richmond, Utah was chosen because it is moderately infested with downy brome and has an abundance of native and naturalized vegetation. The main objectives for this site were to control downy brome and to determine the tolerance of non-target plants, including perennial native forbs, to indaziflam alone and in combination with other herbicides. All treatments including indaziflam reduced downy brome cover in both runs at 7 and 20 months after treatment. Total species richness was reduced with indaziflam treatments, but native species richness was maintained or increased with most treatments including those with indaziflam.

Ventenata is a relatively new invader in the western United States that has only been a significant problem since about the mid-2000s (Wallace and Prather 2016). A site near Mt. Sterling, Utah was chosen because of its recent infestation with ventenata. Because little is known about how ventenata responds to various herbicides, the purpose of this study was to test the effects of different herbicides alone and in combination with indaziflam on ventenata and observe the efficacy of these herbicides for control. In the first run, only treatments with rimsulfuron or indaziflam controlled ventenata in the first year. In the second year, ventenata cover increased in seven of eleven treatments including three of the five indaziflam treatments, but this may have been due to high moisture that year. Glyphosate and imazapic alone were less effective. Overall species richness increased with most indaziflam treatments. Richness was only decreased with imazapic alone. The second run largely mirrored the first. In both trials, aminopyralid nearly doubled ventenata cover due to reductions in broadleaf plants. A greenhouse study was established alongside the field study to test the efficacy of three herbicides: rimsulfuron, imazapic, and glyphosate at increasing rates on three invasive annual grasses: ventenata, medusahead, and downy brome in a controlled environment. Rimsulfuron reduced dry biomass of all grasses at the most rates. Glyphosate was most ineffective out of all the treatments; however, ventenata proved to be much more sensitive to glyphosate in the greenhouse than in the field. This study suggests that timing in the field contributes to overall herbicide effectiveness just as much as, if not more than physiological response.

Medusahead is an aggressive invasive annual grass that decreases biodiversity, degrades rangelands and wildlife habitat, and contributes to increased fire frequency (Sheley *et al.* 2012; Nafus and Davies 2014). This study was designed to test the efficacy of herbicides alone and in combination with indaziflam on medusahead, and to compare revegetation efforts directly after herbicide application as well as one year after. The trial was designed as a randomized strip-plot design. Both strips for each treatment were sprayed at the same time with one strip being seeded immediately following herbicide treatment, and the other being seeded one year after. The first planting in the first run failed; therefore, both strips were seeded the next year and the second run was seeded as originally planned. Re-seeded species generally established better in the plots treated a year before planting except those treated with indaziflam. Amount of precipitation was positively correlated with establishment.

This research provides insight on how herbicide treatments and combinations affect plant community dynamics in diverse ecosystems infested with different invasive annual grasses. These studies also suggest that application timing in the field contributes to overall herbicide effectiveness just as much as physiological response. There are many environmental factors that are difficult to predict that contribute to treatment effectiveness such as precipitation. Each site is different; climate, vegetation, and moisture should all factor into management plans. These studies and others provide understanding on how herbicides including indaziflam affect diverse plant communities under a variety of conditions, and how to better manage invasive grasses and revegetate degraded sites.

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