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The Effect of Indaziflam on Seed Production in Perennial Cool-Season Grasses

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THE EFFECT OF INDAZIFLAM ON SEED PRODUCTION IN PERENNIAL COOL-SEASON GRASSES

by

Benson F. Israelsen

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

of

MASTER OF SCIENCE

in

Plant Science

Approved:

J. Earl Creech Major Professor	Corey V. Ransom Committee Member
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UTAH STATE UNIVERSITY
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ABSTRACT

The Effect of Indaziflam on Seed Production in Perennial Cool-Season Grasses

by

Benson F. Israelsen, Master of Science

Utah State University, 2024

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Department: Plants, Soils, and Climate

Annual invasive grass weeds are a major problem in grass seed production as they contaminate seed lots and decrease the quality. Few effective herbicides are available to control invasive grass weeds in seed production systems. Indaziflam is a pre-emergence herbicide capable of providing annual weed control for 3-5 years after application. Indaziflam is not labeled for use in seed production as little is known of the effect it will have. The purpose of this study was to measure total seed yield, seed germination, seed mass, and seedling vigor when applying 0, 40, 77, and 93 g ai ha^{-1} of indaziflam to existing perennial cool-season seed fields in northern Utah, U.S.A. Two years of data was collected on 11 different species (12 cultivars). Control of annual weeds was excellent in treated plots. Year two of the study showed a decrease in total seed production and seedling vigor in all levels of indaziflam, including the control. Seed germination was not affected and seed mass increased slightly in year two in all levels of indaziflam. Year one was dry and hot while year two was wet and slightly cooler. Additional research is needed to test different environmental conditions that may cause indaziflam to have a negative effect on the above-mentioned traits. (49 pages)

PUBLIC ABSTRACT

The Effect of Indaziflam on Seed Production in Perennial Cool-Season Grasses

Benson F. Israelsen

Annual invasive grass weeds are a major problem in grass seed production as they contaminate seed lots and decrease the quality. Few effective herbicides are available to control invasive grass weeds in seed production systems. Indaziflam is a pre-emergence herbicide capable of providing annual weed control for 3-5 years after application. Indaziflam is not labeled for use in seed production as little is known of the effect it will have. The purpose of this study was to measure total seed yield, seed germination, seed mass, and seedling vigor when applying 0, 40, 77, and 93 g ai ha^{-1} of indaziflam to existing perennial cool-season seed fields in northern Utah, U.S.A. Two years of data was collected on 11 different species (12 cultivars). Control of annual weeds was excellent in treated plots. Year two of the study showed a decrease in total seed production and seedling vigor in all levels of indaziflam, including the control. Seed germination was not affected and seed mass increased slightly in year two in all levels of indaziflam. Year one was dry and hot while year two was wet and slightly cooler. Additional research is needed to test different environmental conditions that may cause indaziflam to have a negative effect on the above-mentioned traits.

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INTRODUCTION

Commercial grass seed production in the United States began in the late 1920’s when the first commercial grass seeding in cultivated rows was accomplished using crested wheatgrass (*Agropyron cristatum* L.) (Rogler et al., 1961). Some of the first European settlers to the Americas carried with them grass seed originating from their homeland pastures and hay fields (Ehlke and Undersander, 1990). Those grasses included orchardgrass (*Dactylis glomerata* L.) and timothy (*Phleum pratensis* L.) (Brown, 1979). As these settlers moved further west to the open prairies, livestock were permitted to graze and farming operations began to cultivate the ground, leading to the destruction of native prairies (Ehlke and Undersander, 1990). It wasn’t until after the Dust Bowl of the 1930’s that grass seed production became an important crop (Ehlke and Undersander, 1990). In 1932, commercial grass seed production fields were observed more frequently in the western United States. By 1942, grasses native to the Great Plains, such as switchgrass (*Panicum virgatum* L.) and sideoats grama [*Bouteloua curtipendula* (Michx.) Torr.] were being grown commercially (Rogler et al., 1961). As commercial grass seed production increased, its goal was to provide high quantity and quality seed to support private and public managers needs to seed rangelands and irrigated pastures (Fowers and Mealor, 2020).

The ability to remove weed seed from commercial seed lots through the cleaning process varies by species and seed size (morphology) (Harmond et al., 1960). When present in grass seed production fields, annual invasive grasses such as cheatgrass (*Bromus tectorum* L.), Japanese brome (*Bromus japonicus Thunb*.), and medusahead

[*Taeniatherum caput-medusae* (L) Nevski], are a major concern as competition from these annual invasive grasses reduce seed yields while the ability to remove them through seed cleaning may result in the failure of the seed field (seed lot) to meet seed certification standards of the Association of Official Seed Analysts (AOSA) (Horton et al., 1990; Hoag et al., 2001). Due to this contamination with annual invasive species, entire seed lots are not marketable causing significant economic hardship to the producer and the user’s inability to purchase the desired seed. In Utah, downy brome (cheatgrass), quackgrass [*Elymus repens* (L.) Gould], barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], green foxtail [*Setaria viridis* (L.) Beauv.], and other cultivated grasses are problems in establishing grasses for production of certified seed (Horton et al., 1990). According to Utah Crop Improvement Association (UCIA) guidelines, row spacing for grass seed production is recommended to be 76 to 91 cm to facilitate weed control and inspection of off-type species (UCIA, 2015). As a result of wide row spacings annual invasive grasses can invade seed fields more easily. Each state has their own list of noxious weeds that are prohibited in seed lots, as well as guidelines of how many seeds of other species are permitted to certify seed lots. For example, cheatgrass, though not considered noxious in Utah, is a common contaminant in many seed lots, and any seed lot with 2% or more of weed seeds by weight cannot be sold or distributed in the state (U.S. Department of Agriculture, 2024). Seed contamination can, therefore, lead to increased costs in post-harvest due to increased processing to remove noxious and invasive weed seeds (Hoag et al., 2001).

The ability to control weeds in the field can significantly reduce the amount of weed seeds in harvested seed lots. Broadleaf weeds are in a different taxonomic family from grass species and are typically easier to control when using a selective herbicide labeled for broadleaf weeds such as 2,4-dichlorophenoxyacetic (2,4-D). However, some broadleaf weeds such as field bindweed (*Convolvulus arvensis* L.), prickly lettuce (*Lactuca serriola* L.), Canada thistle (*Cirsium arvense* (L.) Scop.), and redroot pigweed (*Amaranthus retroflexus* L.) can be challenging to control with commonly used herbicides (Colquhoun et al., 2001). These weed seeds are smaller than grass seeds making them difficult to remove during the cleaning process.

Historically, weed management in grass seed production fields incorporates cultural, mechanical, chemical, or biological control methods (Fowers and Mealor, 2020). Chemical control can be both effective and challenging to employ, especially when attempting to control invasive annual grasses, such as cheatgrass, in a grass production system (Fowers and Mealor, 2020). The most widely used classes of herbicides for invasive annual grass control are amino acid synthesis inhibitors and photosynthetic inhibitors, and within these classes, glyphosate, imazapic, and tebuthiuron are currently used (Rinella et al., 2017). However, in addition to damaging target invasive grasses, amino acid synthesis inhibitors and photosynthetic inhibitors often damage desirable grasses present in the field (Whitson and Koch, 1998). Growth regulators, such as 2,4-D, are regularly used for broadleaf weed control (Rinella et al., 2017). Preemergence herbicides labeled for grass seed production are used in the fall and spring prior to germination to control grass weeds. However, in the spring by the time the ground is dry enough and equipment can enter the field, winter annual weeds like downy brome have already begun to grow, making the preemergence treatments ineffective. Preemergence herbicides can still be applied to control summer annuals such as green foxtail and witchgrass (*Panicum capillare* L.) that have not germinated. A potential emerging tool for annual weed management in seed production systems is indaziflam due to its late summer early fall application and longevity (Fowers and Mealor, 2020).

Indaziflam is a group 29 herbicide and its mode of action is cellulose-biosynthesis inhibition (CBI) that specifically targets root elongation (Fowers and Mealor, 2020). Indaziflam is the active ingredient in preemergence herbicides like Esplanade 200 SC. Esplanade 200 SC is labeled for control of many annual grasses and broadleaf weeds in railroad, roadside, hardscapes, industrial areas, utilities, airports, government and military installations, and managed areas such as pumping stations, storage areas, lumberyards, non-irrigation ditch banks, fence rows. Necrosis or yellowing may also be observed if the herbicide is applied to herbaceous tissue such as leaves and green stems of susceptible plants. For maximum activity against germinating weeds, indaziflam requires rainfall (minimum 6 mm) within several weeks after application to activate the herbicide. Indaziflam has minimal post-emergence activity and generally does not control weeds that have emerged. A post-emergence herbicide such as glufosinate may be mixed with indaziflam to control existing perennial weeds. Indaziflam does not control plants that propagate through tubers, rhizomes, and woody vegetation since they do not produce a root radical (EPA, 2020). Indaziflam is a herbicide that remains within the top few centimeters of the soil leading to impacts only on the plants with roots within that zone (Alonso et al., 2011). Roots of germinating seedlings would be fully exposed to the herbicide within the affected soil whereas perennial roots would persist beneath the indaziflam zone; however, the depth of the zone depends on soil texture and precipitation. Coarse-textured soils with high sand content may result in greater perennial plant root length density injury than would occur in finer-textured soils with more organic matter (Jones et al., 2013). Indaziflam leachability is low to moderate in Oxisols and Mollisols soils due to its low solubility (Alonso et al., 2011). Indaziflam has a soil half-life of >150 days (Tompkins, 2010) and has also been observed to provide 83–100% annual grass control 3-yr after application (Sebastian et al., 2016). Multiple reports suggest the longevity of cheatgrass seed in the soil is <5 yr (Young et al., 1969; Burnside et al., 1996; Smith et al., 2008). The ability to control annual invasive grasses for multiple years with one herbicide application at a low use rate may lead to reduced applications by managers over time with adequate weed control (Sebastian et al., 2017a; Fowers and Mealor, 2020).

Indaziflam has a longer soil residual than other herbicides commonly used for *B. tectorum* management, providing 3 or more years of control (Sebastian et al., 2016; Sebastian et al., 2017a). Sebastian et al. (2016, 2017a) found that indaziflam can selectively control *B. tectorum* without impacting perennial grass and forb biomass, even leading to significant increases in biomass due to reductions in *B. tectorum* (Sebastian et al. 2016, 2017a). Reducing *B. tectorum* abundance can lead to increases in perennial grass and forb abundance as the competition for resources is removed (Monaco et al., 2017; Sebastian et al., 2016; Sebastian et al., 2017a; Thill et al., 1984; Whitson and Koch, 1998); therefore, increasing species abundance in indaziflam and imazapic treatments are likely due to the reduction in *B. tectorum* cover. *B. tectorum* control with indaziflam at 58 g ai ha^{-1} lasted 3 yr with no injury to crested wheatgrass [*Agropyron cristatum* (L.) Gaertn.] and western wheatgrass [*Pascopyrum smithii* (Rydb.) Á. Löve] or impacts to forb species richness (Sebastian et al. 2016). Another study by Sebastian et al. (2017a) reported 2 yr of *B. tectorum* control from indaziflam (44, 73, and 102 g ai ha^{-1}), with increased perennial grass and forb biomass and no impact to forb species richness. Data from Clark et al. (20190 corroborates previous findings of native species tolerance to indaziflam applications, while also showing that the community composition and abundance of native species is not impacted. Integrating indaziflam into current management programs could provide the length of *B. tectorum* control needed to deplete the invasive annual grass seedbank and release the remnant plant community (Chambers et al., 2014; Elseroad and Rudd, 2011; Sebastian et al., 2017b). Currently, indaziflam is not labeled for use in seed production systems so there is a need to evaluate it in a grass seed production setting to test the effects of varying rates of indaziflam on seed production, seed viability, seed vigor, and seed mass of selected perennial cool-season grasses used for rangelands and pastures in the Intermountain West, USA.

MATERIALS AND METHODS

Plant Materials

Cool-season perennial grass species (11) and cultivars (12) used in this study with their common and Latin names along with the location planted, planting date, and release documentation are listed in table 1. All sites were previously planted Foundation seed fields currently in the USDA-ARS Forage and Range Research Unit (FRR) stock seed program. A brief description of each cultivar used is given below.

Table 1
List of perennial grass species with Latin and common names, cultivar, planting year and location. Reference is the release notice of the cultivar.

Species	**Cultivar**	**Location**	**Planting Year**	**Reference**
Basin wildrye *Leymus cinereus* (Scribn. & Merr) Á. Löve	Trailhead II	1	2016	(Robins and Bushman, 2016)
Bluebunch wheatgrass *Psuedoroegneria spicata* (Pursh) Á. Löve	Columbia	2	2017	(Jones and Mott, 2016)
Bottlebrush squirreltail *Elymus elymoides* (J.G. Smith) Barkworth	Turkey Lake	2	2020	(Jones, 2016)
Crested wheatgrass *Agropyron desertorum* (Fisch. ex Link) J.A. Schultes	Hycrest II	1	2008	(Jensen et al., 2009a)
Green *Needlegrass* *Nassella viridula* (Trin.) Barkworth	Cucharas	3	2019	(Jones et al., 2004)
Meadow bromegrass *Bromus riparius* (Rehmann)	Cache	1	2010	(Jensen et al., 2004)
NewHy RS Hybrid wheatgrass *Elymus hoffmannii*	NewHy	1	2018	(Asay et al., 1991)
Orchardgrass *Dactylis glomerata* (L.)	Yeti	3	2020	(Robins et al., 2023)
Siberian wheatgrass *Apropyron fragile* (Roth) Candargy	Stabilizer, Vavilov II	1 2	2018 2018	(Jensen et al., 2013) (Jensen et al., 2009b)
Snake River wheatgrass *Elymus wawawaiensis* (J. Carlson & Barkworth)	Discovery	3	2013	(Jones, 2008)
Thickspike wheatgrass *Elymus lanceolatus* (Scribn. & J.G. Sm.) Gould	Bannock II	2	2017	(Robins et al., 2015)

Location 1, Richmond, UT, Location 2, Hyde Park, UT, Location 3, North Logan, UT

Basin wildrye

‘Trailhead II’ basin wildrye is a tetraploid (2n = 4x = 28; JJNN) cultivar released for use in re-vegetation efforts on rangelands of western USA (Robins and Bushman, 2016). Trailhead II is the result of 2 cycles of recurrent selection originating from the basin wildrye cultivar Trailhead, which originated from collections made in Musselshell County, MT (Cash et al., 1998). Selection emphasis in Trailhead II was rapid seedling emergence from a deep planting depth (Robins and Bushman, 2016). It is adapted to areas with an average annual precipitation of 250 mm where it is moderately tolerant of alkaline and saline soils in the western USA (Asay, 1987).

Bluebunch wheatgrass

Columbia bluebunch wheatgrass germplasm (2n = 4x = 28; StStStSt) was developed through 5-cycles of selection, primarily for increased spike number, directly from collection K68, a population collected in 1980 in Adams County in eastern Washington US (Jones and Mott, 2016). Bluebunch wheatgrass is native to North America (Stebbins Jr and Pun, 1953) where it inhabits dry mountain slopes at middle elevations associated with sagebrush, Gamble oak, and pinyon-juniper vegetation common in the northern Great Plains and Intermountain regions of the western USA receiving between 280 and 450 mm of annual precipitation (USDA-NRCS, 2023).

Bottlebrush squirreltail

Bottlebrush squirreltail germplasm Turkey Lake ssp. *californicus* [J.G. Smith Barkworth (Poaceae)] was released as a selected class of pre-variety germplasm (natural track) (Jones, 2016). This plant material originates in the Idaho’s Snake River Plain in Gooding County in southern Idaho US (Jones, 2016). Bottlebrush squirreltail is a shortlived perennial grass that acts as an early seral species by competing with and replacing annual weedy species immediately following wildfires (USDA-NRCS, 2023). This subspecies can be found inhabiting dry, often rocky regions associated with mid-montane to arctic-alpine in western North America

Crested wheatgrass

‘Hycrest II’ crested wheatgrass (2n = 4x = 28; PPPP) was selected for improved seedling establishment under drought where it is intended for use on arid and semiarid rangelands as a rapid establishing revegetation grass that competes with annual invasive weeds (cheatgrass, medusahead, Halogeton) in the Intermountain Region and Northern Great Plains of the western US (Jensen et al., 2009a). Crested wheatgrass is adapted to disturbed semiarid rangelands that receive between 250 and 380 mm of annual precipitation.

Green needlegrass

Cucharas green needlegrass germplasm, also known as western needlegrass, was released as a selected class of certified seed (natural track) (Jones et al., 2004). Cucharas originated from a collection near Cucharas Junction, Huerfano County, CO, USA. Cucharas was chosen from other green needlegrass collections because of its high productivity and seed yield (Jones et al., 2004). Green needlegrass frequently occurs in western juniper woodlands on dry to moderately moist slopes and ridges in sagebrush environments (USDA-NRCS, 2023).

Meadow bromegrass

‘Cache’ meadow bromegrass (2n = 10x =70) (Jensen et al., 2004) is adapted to the northern tier of the USA and the southern tier of Canada (Majerus, 2009) where its intended use is on irrigated and semi-irrigated pastures receiving greater than 330 mm of annual precipitation (Jensen et al., 2004); (Ogle et al., 2011).

NewHy

The cultivar NewHy (RS hybrid wheatgrass/Hoffman wheatgrass) is a quackgrass (*Elytrigia repens* (L.) Nevski; $2n = 6x = 42$; StStStStHH) X bluebunch wheatgrass, ($2n = 4x = 28$) hybrid. The original hybrid was subjected to 8-cycles of selection for seed production, seedling vigor, and forage production. Taxonomically, NewHy was later described in the species complex of *Elymus hoffmannii* (Jensen and Asay, 1996) where it can be found today. This cultivar is recommended for range sites with moderate salinity soils that receive at least 330 mm of annual precipitation (Asay et al., 1991).

Orchardgrass

The cultivar 'USDA-Yeti' orchardgrass was essentially derived from USDA-UTWH-102 germplasm, which originated from high elevation orchardgrass collections from central/southern UT mountains. USDA-Yeti combines excellent winterhardiness and herbage dry mass with good nutritive value for use on sites that possess risk of orchardgrass winter injury and mortality (Robins et al., 2023). USDA-Yeti intended use is for high elevation irrigated pastures where winter injury frequently occurs due to low temperatures.

Siberian wheatgrass

'Vavilov II' Siberian wheatgrass ($2n = 4x = 28$; PPPP) was developed for reseeding sandy soils on disturbed rangelands dominated my annual weeds due to severe disturbance, frequent fires, and soil erosion. Selection emphasis in Vavilov II was on seedling establishment and stand persistence (Jensen et al., 2009b). Siberian wheatgrass is recommended for semiarid ecological sites receiving between 150 to 300 mm of annual precipitation (Jensen et al., 2009b).

‘Stabilizer’ Siberian wheatgrass (2n = 4x = 28; PPPP) is a unique low-growing cultivar that maintains its blue-green color throughout the growing season and produces less forage than other Siberian wheatgrass cultivars (Asay et al., 1995; Jensen et al., 2009b). Its intended use is on arid and semiarid rangelands as a low-growing, rapid establishing revegetation grass for use on roadsides and as a grass component in fire-strip plantings in the Intermountain West, Great Basin, and Northern Great Plains Regions of the western US (Jensen et al., 2013).

Snake River wheatgrass

‘Discovery’ Snake River wheatgrass (2n = 4x =28; StStHH) traces its origin to collections from Whitman and Asotin Countries in southeastern Washington and Idaho County in central Idaho. Due to its increased seedling establishment and persistence, Discovery is intended for use on rangeland seedlings (Jones, 2008). It is found inhabiting medium-textured soils in arid and semiarid steppe, shrub steppe, and open woodland communities receiving between 300 and 450 mm of annual precipitation. It is the dominate grass in the Columbia and Snake River plains.

Thickspike Wheatgrass

‘Bannock II’ thickspike wheatgrass (2n = 4x = 28; StStHH) is a 5-clone synthetic, resulting from hybridization among selected genotypes of thickspike wheatgrass cultivars ‘Bannock’ and ‘Schwendimar’ (Robins et al., 2015). Its perennial nature, rhizomatous growth habit, more rapid seedling establishment, increased seed production, and drought tolerance make it an important component of many semiarid (200-350 mm annual precipitation) rangeland revegetation seed mixes in the northern Great Basin (Robins et al., 2015).

Site Characteristics

Research was conducted at three locations in Northern Utah, USA. All three locations are in the Central Basin and Range Level III ecoregion. Land use is identified as irrigated cropland with alfalfa, barley, wheat, silage corn and pastures (EPA, 2024). Environmental conditions across the region are typified by a mean low of -6˚C in January to a mean high of 22˚C in July, with an average mean rainfall of 457 mm (Figure 1) (PRISM Climate Group, 2023). Soil order at each location is classified as Mollisols (Boettinger, 2009).

Site 1 (North Logan) was located 6 km northeast of Logan Utah (41.7864921, -111.8175743) at 1,371 m above sea level (ASL), receives 460 mm of average annual precipitation (AAP) (Figure 2) (PRISM Climate Group, 2023). Soil is classified as Millville silt loam (Soil Survey Staff, 2023).

Site 2 (Hyde Park) was located 8 km north of Logan UT (41.8127807, -111.8217478) at 1,387 m ASL, receives 466.5 mm of AAP (Figure 2) (PRISM Climate Group, 2023). Soil is classified as Nibley silty clay loam (Soil Survey Staff, 2023).

Site 3 (Richmond) was located 21 km north of Logan UT (41.8885897, -111.8278163) at 1,379 m ASL, receives 459 mm of AAP (Figure 2) (PRISM Climate Group, 2023). Soil is classified as Nibley silty clay loam (Soil Survey Staff, 2023).

Average 30-year temperatures were slightly lower (Figure 1) than the average temperatures during the study (Figure 2), whereas the 30-year average precipitation (Figure 1) and year 2022 total precipitation were lower than in 2023 (Figure 2).

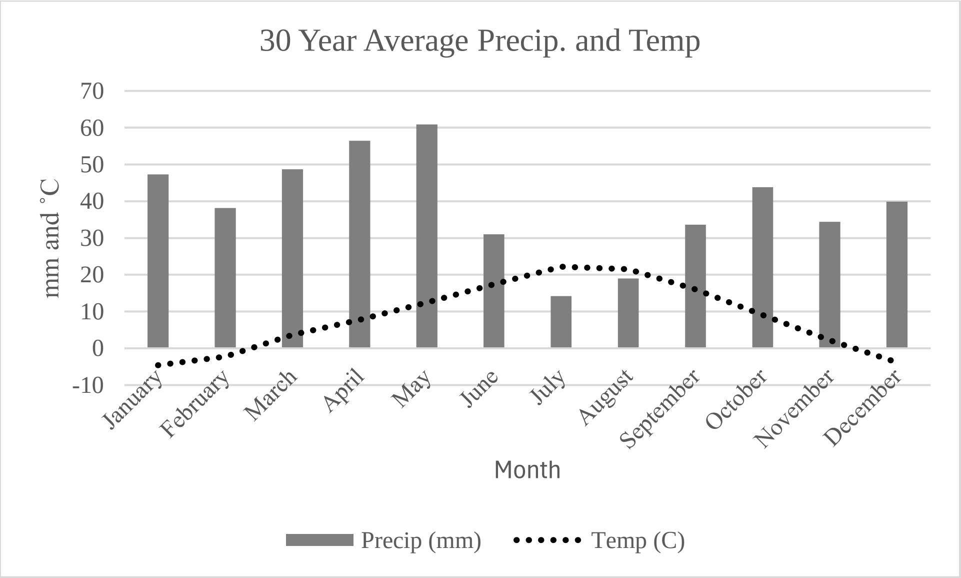

Figure 1: 30-year precipitation and temperature averages for all three locations. All locations are similar. Data last accessed 25 August 2023 at https://www.prism.oregonstate.edu.

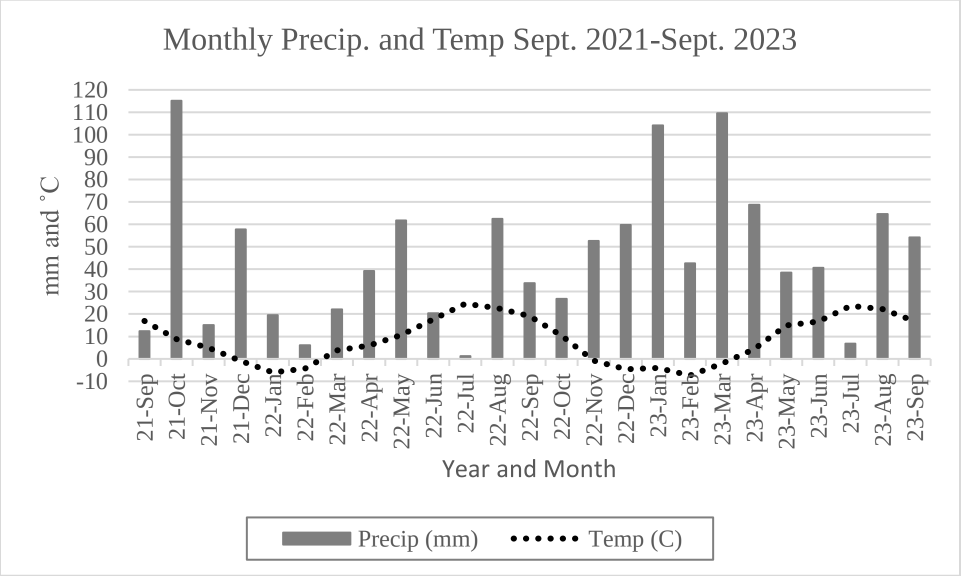

Figure 2: Total monthly precipitation and average temperature from application date September 2021 to end of harvest 2023 for all three locations. All locations are similar. Data last accessed August 25, 2023 at https://www.prism.oregonstate.edu.

Site Preparation and Layout

Prior to herbicide application, all seed fields were roto-tilled between the seed rows in the fall to incorporate plant residue left over after harvest. A pitchfork was used to dispose of residue that was not incorporated. Per the Esplanade label, the soil surface where indaziflam is applied needs to be free of plant residue to ensure soil contact with the chemical. All seed fields had been established for at least two years prior to indaziflam application, except for cultivars Turkey Lake and USDA-Yeti that were planted a year prior (Table 1). Cultivars were planted using a John Deere four-row 71 series flex-i-planter (John Deere Inc. Moline, IL) with row spacings of 91.5 cm. Plot size for each treatment was 2.7 m x 9.1 m with four replications for each location and cultivar, except for USDA-Yeti with only three replications. Plots were arranged in a randomized complete block with treatments of three different rates of indaziflam and a control with no indaziflam applied.

Site Treatments

A custom-built sprayer mounted on four bicycle wheels (Morris et al., 2009) with a boom length of 4 m with 10 nozzles spaced 43.2 cm apart was used to apply indaziflam. A walking speed of 5 km/hr was used to apply 40 g ai ha^{-1}, 77 g ai ha^{-1} and 93 g ai ha^{-1} of indaziflam to plots, except for the control (check) plots. A total of five rows in each plot received treatment, but only the center three rows were harvested. Based on the label, for best results indaziflam should be applied early fall or spring prior to seed germination (EPA, 2020). The North Logan location received herbicide application on 2 September

2021, while Hyde Park and Richmond locations were sprayed on 7 September 2021 prior to fall germination of annual invasive grasses.

Site Maintenance

In the spring of both years, the entire plot area at each location, except North Logan, were sprayed with a 2,4-D herbicide at 2,240 g/ha to control perennial broadleaf weeds. Fields were sprayed while desirable plants were in the vegetative stage and prior to boot. The North Logan location was sold to development after indaziflam application, therefore received no 2,4-D herbicide, irrigation, or fertilizer during the study. Indaziflam has little to no effect on perennial or already growing plants and weeds (EPA, 2020). A string trimmer (Makita U.S.A Inc. La Mirada, CA) was used to control grass weeds between each row in all plots. Trimming was done several times throughout the growing season. All cultivars received 12 hours of sprinkler irrigation at least once during each growing season, except for Discovery, Cucharas, Yeti which were at the North Logan location and Trailhead II because no water was available. Depending on the severity of broadleaf invasion a second application of 2,4-D herbicide was applied later in the growing season before seed set. Fertilizer at a rate of, 80 kg/ha of nitrogen and 22.4 kg/ha of phosphorus was applied each fall to all seed fields in Richmond and Hyde Park during the study.

Harvest

A small plot combine (Wintersteiger Inc. Salt Lake City, UT) was used to harvest the three middle rows of each plot of each cultivar and germplasm. Cultivars and germplasms were harvested based on seed maturity. The two border rows were used to set the correct fan and threshing speed on the combine. The appropriate combine settings were used for the different cultivars harvested. Combine settings were kept constant through all treatments and replications of each cultivar harvested. A ¼ barrel brown paper bag (Uline, Pleasant Prairie, WI) was used to collect the harvested seed from each plot. Harvest dates for the two years of the study and for the different cultivars and germplasms are included in Table 2.

Table 2
Harvest dates of each cultivar and germplasm for the years 2022 and 2023.

Species	**Harvest Dates** Cultivar	Year	
		2022	2023
Green needlegrass	Cucharas	6-Jul	20-Jul
Orchardgrass	‘USDA-Yeti	8-Jul	-
Snake River wheatgrass	‘Discovery’	15-Jul	20-Jul
Bottlebrush squirreltail	Turkey Lake	8-Jul	-
Bluebunch wheatgrass	Columbia	28-Jul	20-Jul
Siberian wheatgrass	‘Vavilov II’	4-Aug	14-Aug
Thickspike wheatgrass	‘Bannock II’	22-Jul	-
Meadow bromegrass	‘Cache’	14-Jul	20-Jul
Crested wheatgrass	‘Hycrest II’	4-Aug	14-Aug
Siberian wheatgrass	‘Stabilizer’	28-Jul	1-Aug
NewHy hybrid wheatgrass	‘NewHy’	4-Aug	1-Aug
Basin wildrye	‘Trailhead II’	27-Jul	31-Jul

Cleaning and Analysis

Harvested seed was weighed immediately following harvest for a wet sample weight (g plot^{-1}) using a portable Ohaus scale (Ohaus Corp. Parsippany, NJ). Following harvest, all seed from each plot was left in their individual brown paper bag and allowed to air dry to a constant weight with fans to keep air moving over the bags. Twice a day seed was stirred by hand for uniform drying for one to two weeks depending on the amount of seed in each bag. Once the seed dried to a constant weight it was weighed for a dry sample weight (g plot^{-1}). The seed was cleaned by hand with seed cleaning screens (SeedBuro Equipment Co. Des Plaines, IL) to remove debris. To ensure high quality seed, a tabletop seed-blower was used to remove chaff and light seeds from the seed lot after screening. Clean seed was again weighed (g plot^{-1}) to obtain the total clean seed yield for each plot and then extrapolated to kg ha^{-1} of seed.

To estimate variation in seed structure, 100-seeds from each plot were analyzed by a seed analyzer (Marvitech Seed Analyzer, Blue Sun Scientific, Jessup, MD) for seed length (mm), width (mm) and weight (mg) of each individual seed, as well as thousand seed weight (TSW; g 1000-seeds^{-1}). Estimates of TSW were based on the weight of 100 seeds. Seed from the seed analyzer were subsequently placed on wetted blotter paper in a 11x11x3.5 cm clear polystyrene germination box (Hoffman Manufacturing, Inc. Corvallis, OR) and placed in a growth chamber (Conviron, Pembina, ND) following germination protocol established by AOSA for each species. Total germination days required ranged from 21-28 days depending on the species. Percentage germination was recorded for each plot. Seedling vigor was evaluated through the ability of seedlings to emerge from a deep planting depth. To determine the seedling vigor (Maquire, 1962) 100-seeds from each cultivar, treatment, and replication were planted at a seeding depth of 7.6 cm. Because of its small seed size compared to the other cultivars, USDA-Yeti was planted at 1.3 cm deep. The soil substrate consisted of 3:1 sand and peat moss. Seedling emergence was counted once every seven days for a period of 3 weeks to determine rate of emergence (Maquire, 1962). Two years' worth of data was collected and analyzed except for Yeti, Turkey Lake and Bannock II.

Statistics

All data were subjected to analysis of variance by GLM procedures with a random statement. Respective mains effects were tested for significance using the appropriate main effect by replication interaction (SAS_Institute, 1994). Mean separations were made on the basis of least significant differences (LSD) at the 0.05 probability level (SAS_Institute, 1994). Within species, all data was found to be normally distributed based on Shapiro-Wilks test (SAS_Institute, 1994). Linear, quadratic, and cubic trends of indaziflam rates were determined for each species using orthogonal polynomials with equal year intervals (Gomez and Gomez, 1984).

RESULTS

Total Seed Yield (Clean Seed)

Due to differences inherent between species in the study for total seed yield, size, and morphology etc., we did not compare these traits across species; therefore, the results are reported by cultivar within species. A non-significant total seed yield by year interaction in all cultivars except for Vavilov II Siberian wheatgrass ($P < 0.05$), suggests that differences in total seed yield between 2022 and 2023 were more of a magnitude shift rather than a rank change between levels of indaziflam (Table 3). Thus, data for total seed yield will be combined over years. Regardless of cultivar, the level of indaziflam had little to no effect on total seed yield in all cultivars studied except Cucharas green needlegrass (Table 4). Based on orthogonal polynomial contrasts, there was a significant ($P < 0.05$) linear effect suggesting that as levels of indaziflam increased so did total seed yield in Trailhead II basin wildrye and Cucharas (Table 4). Apart from Stabilizer Siberian wheatgrass ($P = 0.1259$), a significant ($P < 0.05$) year affect was observed in all cultivars for total seed yield (Table 3). Trailhead II and RS Hybrid cv. NewHy were the only cultivars to increase total seed yield ($P < 0.05$) at 25 and 72%, respectively, from 2022 to 2023, while the remainder of the cultivars had a decrease in total seed yield ($P < 0.05$). Cultivar rankings from least to the greatest decrease in total seed yield from 2022 to 2023 were Cache meadow bromegrass (17%), Hycrest II crested wheatgrass (20%), Vavilov II (37%), Stabilizer (41%), Columbia bluebunch wheatgrass (55%), NewHy (73%), Discovery Snake River wheatgrass (80%), and Cucharas (83%) (data not shown). The overall lack of significant differences within cultivars in both 2022 and 2023 between the control and levels of indaziflam may imply that increasing levels of indaziflam had little to no effect on total seed yield, regardless of species except for bottlebrush squirreltail (Turkey Lake) where stand frequency in 2023 was near zero.

Table 3

ANOVA for seed yield, seed germination, 1000-seed weight, and seedling vigor as affected by indaziflam rates of 0, 40, 77,and 93 g ai ha^{-1}.

Meadow brome		P-Value	
Trait	Treatment (T)	Year (Y)	T X Y
Seed yield (kg plot-1)	0.7282	0.0197	0.3892
Seed germination (%)	0.3	0.0481	0.0011
1000-seed weight (g)	0.8148	0.001	0.3217
Seedling emergence	0.6664	0.1055	0.3505

Hycrest II		P-Value	
Trait	Treatment (T)	Year (Y)	T X Y
Seed yield (kg plot-1)	0.1437	0.0055	0.7699
Seed germination (%)	0.0038	0.0533	0.0092
1000-seed weight (g)	0.4512	0.005	0.1365
Seedling emergence	0.0312	0.0191	0.4308

Stabilizer		P-Value	
Trait	Treatment (T)	Year (Y)	T X Y
Seed yield (kg plot-1)	0.2215	0.1259	0.7151
Seed germination (%)	0.6902	0.006	0.4613
1000-seed weight (g)	0.059	0.0024	0.0975
Seedling emergence	0.0183	0.3958	0.1273

Columbia		P-Value	
Trait	Treatment (T)	Year (Y)	T X Y
Seed yield (kg plot-1)	0.9546	0.0081	0.2067
Seed germination (%)	0.7567	0.0549	0.5245
1000-seed weight (g)	<0.0001	0.0231	0.6187

Discovery		P-Value	
Trait	Treatment (T)	Year (Y)	T X Y
Seed yield (kg plot-1)	0.1908	0.0044	0.075
Seed germination (%)	0.0416	0.0287	0.0313
1000-seed weight (g)	0.7753	0.0011	0.7413
Seedling emergence	0.4685	0.008	0.3525

NewHy		P-Value	
Trait	Treatment (T)	Year (Y)	T X Y
Seed yield (kg plot-1)	0.2078	0.0004	0.4087
Seed germination (%)	0.8034	0.1774	0.0759
1000-seed weight (g)	0.1083	0.0799	0.1716
Seedling emergence	0.7217	<.0001	0.9519

Trailhead II		P-Value	
Trait	Treatment (T)	Year (Y)	T X Y
Seed yield (kg plot-1)	0.4127	0.0017	0.2791
Seed germination (%)	0.2981	0.0006	0.9809
1000-seed weight (g)	0.2783	0.2255	0.3151
Seedling emergence	0.4066	0.0213	0.1082

Vavilov II		P-Value	
Trait	Treatment (T)	Year (Y)	T X Y
Seed yield (kg plot-1)	0.5459	0.0054	0.0107
Seed germination (%)	0.4378	0.0004	0.2984
1000-seed weight (g)	0.7175	0.0009	0.987
Seedling emergence	0.6772	0.1246	0.4697

Cucharas		P-Value	
Trait	Treatment (T)	Year (Y)	T X Y
Seed yield (kg plot-1)	0.3046	0.001	0.7365
Seed germination (%)	0.4332	0.193	0.9806
1000-seed weight (g)	0.053	0.0033	0.7265
Seedling emergence	0.5133	0.0241	0.4569

Table 4

Mean, 2022-2023, total seed yield (kg ha^{-1}) as affected by indaziflam rates 0, 40, 77, and 93 g ai ha^{-1} and orthogonal contrasts over indaziflam levels.

	Rates of Indaziflam (g ai ha^{-1})						Orthogonal contrasts		
Species/Cultivar	**0**	**40**	**77**	**93**	**LSD $_{(0.05)}$**	**2022 vs 2023£**	**Linear**	**Quadratic**	**Cubic**
Meadow brome cv. Cache	511	523	483	501	ns	*	ns	ns	ns
Crested wheatgrass cv. Hycrest II	506	498	520	441	ns	*	ns	ns	ns
Siberian wheatgrass cv. Stabilizer	68	84	63	79	ns	ns	ns	ns	ns
Siberian wheatgrass cv. Vavilov II	479	532	508	474	ns	*	ns	ns	ns
RS Hybrid cv. NewHy	108	104	126	99	ns	*	ns	ns	ns
Thickspike wheatgrass cv. Bannock II	149	169	178	173	ns	-	ns	ns	ns
Snake River wheatgrass cv. Discovery	161	160	168	151	ns	*	ns	*	ns
Bluebunch wheatgrass cv. Columbia	72	68	67	65	ns	*	ns	ns	ns
Basin wildrye cv. Trailhead II	209	228	241	245	ns	*	*	ns	ns
Bottlebrush squirreltail cv. Turkey Lake	112	116	102	74	ns	-	ns	ns	ns
Green needlegrass cv. Cucharas	107	120	131	134	19	*	**	ns	ns
Orchardgrass cv. Yeti	113	143	102	134	ns	-	ns	ns	ns

*, ** Significant at the 0.05 and 0.01 levels of probability, respectively.

£ Significant at ($P < 0.05$) comparing total seed yield between 2022 and 2023

Germination

A non-significant germination (%) by year interaction was observed in all cultivars except for Cache, Hycrest II and Discovery ($P < 0.05$), suggests that differences in total percentage seed germination between 2022 and 2023 were more of a magnitude shift rather than a rank change between levels of indaziflam (Table 3). As mentioned previously, total percentage seed germination data will be combined over years. The level of indaziflam had little to no effect on total percentage seed germination in all cultivars except for Hycrest II, Discovery, and Turkey Lake (Table 5). Based on orthogonal contrasts, there was a significant ($P < 0.05$) negative linear effect in Turkey Lake total percentage seed germination suggesting that as levels of indaziflam increased germination decreased (Table 5). Five cultivars, Cache, Stabilizer, Vavilov II, Discovery, and Trailhead II had a significant ($P < 0.05$) year affect for total percentage seed germination (Table 3). Percentage seed germination for all cultivars from 2022 to 2023 ranged from 92 to 100%, except for Cucharas (60%) (data not shown). The overall lack of significant difference within cultivars in both 2022 and 2023 between the control and levels of indaziflam suggests that increasing levels of indaziflam had little to no effect on seed germination percentage, regardless of species.

Table 5

Mean, 2022-2023, total seed germination (%) as affected by indaziflam rates 0, 40, 77, and 93 g ai ha^{-1} and orthogonal contrasts over indaziflam levels.

	Rates of Indaziflam (g ai ha^{-1})						Orthogonal contrasts		
Species/Cultivar	**0**	**40**	**77**	**93**	**LSD $_{(0.05)}$**	**2022 vs 2023$^{£}$**	**Linear**	**Quadratic**	**Cubic**
Meadow brome cv. Cache	98	98	97	98	ns	*	ns	ns	ns
Crested wheatgrass cv. Hycrest II	96	97	95	98	1.2	ns	ns	ns	**
Siberian wheatgrass cv. Stabilizer	97	95	97	96	ns	*	ns	ns	ns
Siberian wheatgrass cv. Vavilov II	92	93	90	94	ns	*	ns	ns	ns
RS Hybrid cv. NewHy	97	98	98	97	ns	ns	ns	ns	ns
Thickspike wheatgrass cv. Bannock II	99	98	98	98	ns	-	ns	ns	ns
Snake River wheatgrass cv. Discovery	96	98	98	97	1.7	*	ns	**	ns
Bluebunch wheatgrass cv. Columbia	94	94	93	95	ns	ns	ns	ns	ns
Basin wildrye cv. Trailhead II	96	96	96	95	ns	*	ns	ns	ns
Bottlebrush squirreltail cv. Turkey Lake	94	94	93	86	7.4	-	**	ns	ns
Green needlegrass cv. Cucharas	61	57	59	59	ns	ns	ns	ns	ns
Orchardgrass cv. Yeti	94	96	92	92	ns	-	ns	ns	ns

*, ** Significant at the 0.05 and 0.01 levels of probability, respectively.

£ Significant at ($P < 0.05$) comparing total seed yield between 2022 and 2023

Thousand Seed Weight (TSW)

A non-significant ($P < 0.05$) TSW by year interaction was observed in all cultivars for TSW between 2022 and 2023 implying that differences in TSW were more of a magnitude shift rather than a rank change between levels of indaziflam (Table 3). Regardless of cultivar, the level of indaziflam had little to no effect on TSW in all cultivars except Cucharas (Table 6). Based on orthogonal contrasts there was non-significance observed in all cultivars (Table 6). Six cultivars, Cache, Hycrest II, Stabilizer, Discovery, Vavilov II, Columbia and Cucharas all had a significant ($P < 0.05$) year affect for TSW (Table 3). NewHy and Trailhead II were the only cultivars to show a decrease in TSW at 8 to 3%, respectively, from 2022 to 2023, while the remainder of the cultivars had an increase. Rankings of cultivars from least to greatest percent increase in TSW from 2022 to 2023 were Columbia (4%), Hycrest II (9%), Cache (10%), Vavilov II (12%), Stabilizer (13%), and Discovery and Cucharas (14%) (data not shown). The overall lack of significant difference within cultivars in both 2022 and 2023 between the control and levels of indaziflam may indicate that increasing levels of indaziflam had little to no effect on TSW, regardless of species.

Table 6

Mean, 2022-2023, 1000 seed weight (g) as affected by indaziflam rates 0, 40, 77, and 93 g ai ha^{-1} and orthogonal contrasts over indaziflam levels.

	Rates of Indaziflam (g ai ha^{-1})						Orthogonal contrasts		
Species/Cultivar	**0**	**40**	**77**	**93**	**LSD $_{(0.05)}$**	**2022 vs 2023£**	**Linear**	**Quadratic**	**Cubic**
Meadow brome cv. Cache	5.8	5.9	5.8	5.9	ns	*	ns	ns	ns
Crested wheatgrass cv. Hycrest II	3.2	3.3	3.3	3.2	ns	*	ns	ns	ns
Siberian wheatgrass cv. Stabilizer	2.8	2.8	2.8	2.8	ns	*	ns	ns	ns
Siberian wheatgrass cv. Vavilov II	3.1	3	3.2	3.1	ns	*	ns	ns	ns
RS Hybrid cv. NewHy	3.7	3.6	3.4	3.7	ns	ns	ns	ns	ns
Thickspike wheatgrass cv. Bannock II	1.7	2.3	2	2.1	ns	-	ns	ns	ns
Snake River wheatgrass cv. Discovery	3.4	3.4	3.3	3.3	ns	*	ns	ns	ns
Bluebunch wheatgrass cv. Columbia	4.4	4.4	4.4	4.5	ns	*	ns	ns	ns
Basin wildrye cv. Trailhead II	3.4	3.6	3.6	3.7	ns	ns	ns	ns	ns
Bottlebrush squirreltail cv. Turkey Lake	5	4.7	5	5	ns	-	ns	ns	ns
Green needlegrass cv. Cucharas	3.8	3.9	3.9	4	0.16	*	ns	ns	ns
Orchardgrass cv. Yeti	1	1	1	1	ns	-	ns	ns	ns

*, ** Significant at the 0.05 and 0.01 levels of probability, respectively.

£ Significant at ($P < 0.05$) comparing total seed yield between 2022 and 2023

Deep Seeding

A non-significant deep seeding by year interaction in all cultivars suggests that differences in seedling vigor between 2022 and 2023 were more of a magnitude shift rather than a rank change between levels of indaziflam (Table 3). Regardless of cultivar, the level of indaziflam had little to no effect on total seedling vigor in all cultivars except Hycrest II, Stabilizer, and Yeti orchardgrass (Table 7). Based on orthogonal polynomial contrasts, a significant ($P < 0.05$) positive linear effect for Yeti suggests that as levels of indaziflam increased so did total seedling vigor (Table 7). A significant ($P < 0.05$) year effect was observed in all cultivars except Cache, Stabilizer, and Vavilov II (Table 7). Columbia was the only cultivar with no seedling vigor in 2022 and 2023 suggesting that 7.6 cm is too deep for emergence to occur. The overall lack of significance within cultivars in both 2022 and 2023 between the control and levels of indaziflam may indicate that increasing levels of indaziflam had little to no effect on seedling vigor, regardless of species.

Table 7

Mean, 2022-2023, total deep seedling rate of emergence (seedling vigor) as affected by indaziflam rates 0, 40, 77, and 93 g ai ha^{-1} and orthogonal contrasts over indaziflam levels.

	Rates of Indaziflam (g ai ha^{-1})						Orthogonal contrasts		
Species/Cultivar	**0**	**40**	**77**	**93**	**LSD $_{(0.05)}$**	**2022 vs 2023$^{£}$**	**Linear**	**Quadratic**	**Cubic**
Meadow brome cv. Cache	7.1	7.4	7.3	6.8	ns	ns	ns	ns	ns
Crested wheatgrass cv. Hycrest II	2.8	3	3.3	3.2	0.38	*	ns	ns	ns
Siberian wheatgrass cv. Stabilizer	2.9	3.5	2.6	4.1	1	ns	ns	ns	**
Siberian wheatgrass cv. Vavilov II	4.3	4.8	4.6	4.5	ns	ns	ns	ns	ns
RS Hybrid cv. NewHy	2.5	2.2	2.4	2.2	ns	*	ns	ns	ns
Thickspike wheatgrass cv. Bannock II	7.9	8.8	7.9	7.5	ns	-	ns	ns	ns
Snake River wheatgrass cv. Discovery	0.5	0.4	0.4	0.6	ns	*	ns	ns	ns
Bluebunch wheatgrass cv. Columbia	-	-	-	-	-	-	-	-	-
Basin wildrye cv. Trailhead II	2.9	2.3	2.7	2.8	ns	*	ns	ns	ns
Bottlebrush squirreltail cv. Turkey Lake	4.4	5	4.6	4.6	ns	-	ns	ns	ns
Green needlegrass cv. Cucharas	5.1	5	4.9	5.3	ns	*	ns	ns	ns
Orchardgrass cv. Yeti	7.7	10.5	9.2	9	2.67	-	*	ns	ns

*, ** Significant at the 0.05 and 0.01 levels of probability, respectively.

£ Significant at ($P < 0.05$) comparing total seed yield between 2022 and 2023

DISCUSSION

This study shows that increasing indaziflam rates had no effect on total seed production, germination, TSW, and seedling vigor from year to year. According to Fowers and Mealor (2020), controlling annual weeds with indaziflam can potentially increase seed production and should provide a useful tool for annual weed management in established seed production fields. Species-specific responses warrant further research across multiple locations to develop more consistent recommendations for growers in the event that indaziflam is labeled for such uses (Fowers and Mealor, 2020).

Annual weed competition was generally suppressed with all rates suggesting that lower rates are just as effective as higher rates. However, in 2023 visual observations in Vavilov II showed plant injury in plots with higher rates compared to lower rates. Early spring of 2023, vole damage was observed in Vavilov II with tunnels going down the middle of the crop row in each plot. In 2023, Turkey Lake plots were nonexistent in each treated plot with copious amounts of kochia in control plots. Treated plots of Bannock II were infested with field bindweed and control plots had noticeable amounts of cheatgrass, therefore no seed was harvested in 2023. Turkey Lake had only been in seed production for one year prior to herbicide application, suggesting more research is needed to determine the effect of indaziflam on young stands compared to older ones. Bannock II and Turkey Lake were sprayed with a low rate of glyphosate (2% solution) between each row using a backpack sprayer to kill field bindweed following harvest in 2022. It is possible that some glyphosate drifted onto the plots causing crop injury and death, resulting in no harvest in 2023. Yeti was not harvested in 2023 due to loss of the research site to housing development.

Temperatures during both years were nearly the same during the growing season, April to August, with 2023 being slightly cooler and wetter (Figure 2). The application year 2021 fall and winter were dry followed by a hot and dry 2022 growing season. The latter part of 2022 and early part of 2023 were wetter than normal, followed by a cooler than normal May and June. These environmental factors may have contributed to differences from year to year. In March 2022 temperatures at each location were above freezing, whereas in 2023 temperatures did not get above freezing until April. These cooler temperatures may have affected overall seed production in 2023.

Total Clean Seed

Generally, there was a decrease in total seed production from 2022 to 2023 of all species for all treatments. However, no significance was observed in total clean seed yield within years between treatments. Visual observation of seed shatter in Cucharas in 2023 may have contributed to the significance observed with different levels of indaziflam (Table 4). Cucharas was also harvested two weeks later in 2023 than the previous year, whereas the other species were harvested about the same time or one week later in 2023 than in 2022 (Table 2). The fact that total seed yield in the untreated plots in 2023 suggests indaziflam had no effect and environmental conditions may have also been a factor, suggesting more research is needed.

Germination

Generally, seed germination was not affected by indaziflam. This is consistent with findings from Fowers and Mealor (2020). Although there was a significant year effect from 2022 to 2023, all species had excellent germination. Germination percentage greater than 90% is considered excellent when selling and purchasing seed.

Thousand Seed Weight

Significance in TSW observed from 2022 to 2023 was a result of slightly larger seed in 2023. The increase in TSW weight in 2023 may be a result of plentiful precipitation compared to 2022.

Deep Seed Vigor

All cultivars showed a decrease in seedling vigor (rate of emergence) in 2023 compared to 2022. Not all species have been selected for seedling vigor at deep planting depths. However, not all species had a significant year effect. Columbia was the only species where no seeds emerged during both years. Seed size and weight are extremely important characteristics associated with seedling vigor (McKell and Younger, 1972). With larger seeds in 2023, increased seedling vigor might be expected. In 2022, a mixture of peat moss and sand was used as the seed bed media while in 2023, only sand was used. It may be possible that the soil media used influenced the ability for seedlings to emerge. Peat moss and sand mix may have settled more when watered making the planting depth shallower than the straight sand mix. However, seeds are not typically planted 7.6 cm deep.

Yields typically vary from year to year. This variation can be a result of temperature, precipitation, improper settings on harvest equipment, and other factors. Cleaning techniques may not be exactly consistent due to human error which may also affect total clean seed yields. Germination is usually not affected from year to year for any plant species under ideal conditions. However, unfavorable environmental factors may affect seed germination.

Producers must determine the economic advantages and disadvantages of using and not using indaziflam for seed production. They must decide if a potential decrease in seed production, at least during the second year after application, is better or worse than harvesting annual grass weeds with the desired crop.

CONCLUSION

The use of indaziflam in seed production of perennial cool-season grasses appears to control annual invasive weeds. Lower rates of indaziflam appear to be just as effective as higher rates. The decline of total seed production in 2023 compared to 2022 in the control and in all levels of indaziflam suggests the environment and human error may be the cause. Further research is needed to see the effects different weather conditions and environments have on seed production sprayed with indaziflam. Seed germination, TSW, and seedling vigor were not generally affected by indaziflam, even though some traits showed statistical significance.

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