THESIS

USING INDAZIFLAM FOR INTEGRATED WEED MANAGEMENT IN MANAGED AND NATURAL ECOSYSTEMS

Submitted by

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ABSTRACT

USING INDAZIFLAM FOR INTEGRATED WEED MANAGEMENT IN MANAGED AND NATURAL ECOSYSTEMS

Indaziflam is a relatively new herbicide for natural area weed management. It is unique because it inhibits cellulose biosynthesis and it controls annual weeds as the seeds germinate. This soil active herbicide provides the opportunity to control winter annual grasses and annual broadleaf weeds without impacting established perennial grasses and forbs. These characteristics are key to managing weeds, while promoting the growth of native vegetation.

Indaziflam was a key component in the development of an integrated weed management plan for Denver International Airport (DEN). DEN supports a diverse set of landscapes, from the Pena Boulevard Transport Corridor to shortgrass prairie, natural areas, and riparian corridors. DEN is faced with several challenges when managing vegetation, with weed invasion being one of the most important. Kochia (*Bassia scoparia*) and downy brome (*Bromus tectorum* L.) pose the greatest threats to desirable vegetation and healthy, sustainable ecosystems. Kochia is an invasive broadleaf that is a prolific seed producer and can spread quickly. Downy brome is also a highly invasive winter annual grass that can fill open niches in native plant communities. Current vegetation management at DEN does not adequately control weeds and does not promote the growth of desirable vegetation. Therefore, site-specific research assessing passive and active restoration practices was conducted to develop a landscape management plan to help improve and promote native vegetation.

Two research studies were established at DEN, both with remnant native grasses that were also invaded by downy brome and kochia. The objective was to demonstrate passive restoration. We hypothesized that weed control using indaziflam and other post-emergent herbicides would provide 2+ years of control. Downy brome, kochia, and perennial grass cover and biomass were collected in 2019 and 2020 to measure herbicide impacts and plant community responses. Averaged across both sites, downy brome cover, 2 years after treatment (YAT), was reduced to < 2% in all indaziflam plots compared to the control (~75% cover). At both sites, perennial grass biomass increased 5 - to 10 – fold once downy brome competition was removed. These invaded sites with remnant grass populations responded positively with timely weed management. Active restoration was employed at two sites that were void of desirable grass species. Perennial grasses were drill seeded and protected from weed competition with adaptive weed management, primarily with selective herbicides. With adequate weed control and supplemental irrigation, crested wheatgrass was the only grass that successfully established (83% stand frequency). This study illustrates the challenges associated with revegetating degraded sites and the necessity of providing adaptive weed management. Furthermore, the information derived from these studies was used to develop management prioritization categories to assist DEN in making strategic decisions for managing weeds and restoring sites across the airport property. The final management plan represents the culmination of the site-specific, research-based recommendations made and will be utilized by DEN land management to improve current practices. This project also demonstrated the utility of using indaziflam in a managed ecosystem.

In natural ecosystems invaded by downy brome, indaziflam provides similar opportunities for passive restoration. Downy brome produces large amounts of litter in these ecosystems that act as continuous fine fuel. Prescribed burning is often used as a tool to remove

plant litter and provide downy brome control and can be followed by herbicide treatments to extend control; however, combining prescribed burning with indaziflam has not been evaluated. We hypothesized that removing the litter layer using prescribed fire before applying indaziflam alone or combined with post-emergent herbicides would increase herbicide efficacy and extend downy brome control. In September 2017, two downy-brome infested sites were burned. In March 2018, indaziflam was applied alone or in combination with post-emergent herbicides to the burned area as well as non-burned plots. Downy brome cover and the desirable plant community responses were evaluated to determine burning and treatment effects. Downy brome cover was reduced in all herbicide treatments in the burned plots compared to the non-burned plots at both sites 2 years after treatment (YAT) (Site 1 - 6.5% ± 1.2 SE vs. 19.8% ± 2.6; Site 2 - 7% ± 1.5 vs. 15.5% ± 1.7). Desirable plant species cover, richness, and diversity were not negatively impacted by burning or herbicide treatments. Perennial cool-season grass cover responded positively to burning at site 1, while the perennial forb community responded positively to burning at site 2. Plant diversity and species richness also increased at site 2 in the burned plots which was due to the increase in the number of native forb species. This study demonstrates that burning extended downy brome control even at lower indaziflam use rates, without reducing the diversity of the desirable plant community. This research also demonstrates the utility of using indaziflam in natural ecosystems.

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Executive Summary

Denver International Airport (DEN) contracted with Colorado State University (CSU) to create a vegetation management plan for DEN based on on-site research and best management practices. This project began in May 2018 and was completed in October 2020. The main objective of this project was to provide DEN with recommendations and guidelines to help improve weed management and land restoration efforts across diverse airport land types.

DEN property supports a diverse set of landscapes, from the Pena Boulevard Transport Corridor to shortgrass prairie, natural areas, and several riparian corridors. In many cases within this wide range of landscapes, harsh environmental and soil conditions occur that make it difficult for sustainable ecosystems to thrive. The main issue that DEN faces is weed invasion. **Not only are weeds a result of years of disturbance, but they continue to degrade these landscapes to where they no longer support any native vegetation and lack ecosystem sustainability.** Kochia and downy brome are the two most problematic weeds at DEN and are easy to control, although they are very competitive and prolific seed producers. DEN must assume that these two weeds will be an issue in most landscapes, alongside a variety of different biennial and perennial weeds, and will need to be aggressively controlled. Control efforts must be changed to be proactive, rather than cosmetic, short-term, and reactive. Achieving healthy vegetation can reduce maintenance costs, increase roadside safety, and improve essential vegetation growth for aesthetics and overall sustainability.

This plan provides important guidelines, recommendations, and general information that are imperative to restoring the degraded landscapes at DEN. It focuses on how to prioritize sites

for management, best practices for weed control, and improved land restoration practices. The following is a list of key information and recommendations developed over the past two years. Each one of these points is discussed in further detail throughout this plan.

- DEN needs to prioritize weed management in sites with remnant perennial grass communities. These sites are categorized as having 25-75% perennial grass cover but are heavily invaded. Sites with remnant grass communities are likely to respond positively (increased grass cover and biomass) once invasive weeds have been managed. This strategy requires minimal inputs but produces positive results within 1-2 seasons.
- Weed control is the first and most important piece of the land restoration process. Without weed control, seeded and established grasses have little chance of establishing or persisting. It is important to provide adaptive weed management during grass establishment.
- Selective weed control using herbicides is the most cost effective and labor efficient strategy that can be a long-term tool when using products that provide multiple years of weed control. Although no single herbicide or combination is appropriate for all situations, Esplanade (indaziflam) + Method (aminocyclopyrachlor) is an effective, long-term herbicide combination to control downy brome and kochia, in addition to several broadleaf weeds.
- Weed management can be done throughout the year. Many herbicides have soil residual activity that allow them to be applied almost year-round. These products can be applied with glyphosate or with a selective product that controls emerged weeds.

- Mowing is not a selective, or effective, weed management tool. It does not control the weed seed bank, which is necessary for driving these problematic species out of the system. As a non-selective method, it can increase stress on perennial grasses, especially when operations are done during the summer months.
- Mowing perennial grasses in July-September is not an ideal time for actively growing perennial grasses. Mowing operations should be shifted to after perennial grasses have set seed in September to allow for grasses to complete their annual cycle and they start to go dormant. In addition, landside roadside mowing heights should be >8 inches tall to allow for enough aboveground biomass for successful regrowth after mowing and decrease plant stress.
- For a successful weed management program, 1 to 2 employees should be trained to the level of a Qualified Supervisor. This would allow them to handle, mix, and apply herbicides. It would also allow them to train and supervise other DEN employees.
- The most consistent process to establish native grasses requires controlling weeds in the spring, keeping sites weed free during the summer, and drill seeding in the fall. This allows the soil to store moisture before grass germination. Seeding in the spring is possible, but supplemental irrigation must be provided for grasses to establish.
- For sites that are in poor condition (high MgCl, poor quality introduced soil (i.e. topsoil), etc.), it is harder to establish native perennial grasses. Therefore, utilizing grass species that will establish and persist will be more important than native perennial grasses that require more inputs to establish.

The main conclusion from the management plan is that successful vegetation across the airport property depends on an integrated approach that involves best management practices.

There are several issues that DEN faces when trying to restore and maintain roadsides, natural areas, the airfield, and several other areas around the property. The recommended approach to overcome obstacles and improve these environments is to assess and identify existing conditions to determine what the goals are, what management needs to be done, and how to implement these strategies. Using selective herbicides for weed control, using proper seeding techniques, selecting correct plant species for the area, and monitoring sites will greatly affect the success and condition of focus areas. Use of these practices are some of the most important best management practices identified in the management plan.

Background Information

The influx of non-native, invasive species into natural areas is one of the most challenging issues land managers face today, particularly in the Western US. These plants are commonly called weeds and ultimately decrease the ecological integrity of natural systems by decreasing biological diversity and ecological functions. They alter water, energy, and nutrient cycling, decrease community productivity, species richness, and plant diversity (DiTomaso 2000). Invasive weeds are an ongoing issue for both public and private land managers as they threaten to reduce native plant communities and negatively impact ecological functions. As a result of these obstacles created by invasive weeds, management has become an important objective for federal, state, public and private land managers. Developing effective and sustainable practices for vegetation management are extremely important in working towards restoring these ecosystems to a more desirable condition.

The Denver International Airport (DEN) is located in the Central Shortgrass Prairie of northeastern Colorado, northeast of downtown Denver. DEN properties consist of airport facilities, including the airfield and runways, farmland, riparian areas, and short grass prairie. The total area of DEN property is approximately 33,730 acres, of which 10,125 acres resides inside the fence, or the Air Operations Area ("airside"). The remaining 23,605 acres are outside the fence ("landside"). Of these acres located outside the fence, approximately 2,343 acres comprise the Pena Boulevard Transportation Corridor (PBTC). The remaining acres outside the fence are comprised of agricultural land and solar leases(Nissen 2018).

DEN property supports a diverse plant community; however, several compounding factors have greatly impacted the aesthetic and ecological value of the land, creating potential for environmental and, in some cases, economic loss. These factors include excess magnesium chloride applications, prairie dog invasions, erosion, and weed invasion. Each of these factors contributes to creating an unhealthy cycle within these landscapes at DEN.

Land use patterns are very diverse at DEN, providing many mechanisms by which invasive plants can be introduced (Schilling 2013). The diverse nature of shortgrass prairie, agricultural land, airport facilities, and rights-of-way on DEN property creates many non-crop fringe areas. Areas with poor vegetation cover, that are frequently disturbed and manipulated by surrounding land uses are often more susceptible to weed invasion (Hobbs and Humphries 1995; Wilson et al. 2010). These non-crop areas harbor weed seed that can be easily dispersed through movement of vehicles, equipment, soil, wind, water, and wildlife into adjacent areas. Examples of these degraded land areas include roadsides, rights-of-way, crop field margins, water diversions, and water collection ponds. It is important to properly manage these sites for erosion, problematic wildlife, salt accumulation, and weeds to prevent further landscape degradation.

DEN opened for business over 20 years ago and since then, high levels of disturbance and the lack of consistent vegetation management has created optimal conditions for weeds to invade and thrive. Over the last 20+ years, overall landscape health and weed dispersal has become an increasing issue for the airport. To date, land management at DEN has not taken advantage of available technology and resources, and in some cases has damaged native plant communities and soil health. Control efforts are cosmetic (i.e. mowing), short-term, and reactive. Current management practices administered by DEN include mowing and herbicide use, primarily with a non-selective herbicide called glyphosate (RoundUp®). These efforts do not promote native plant growth and require repeated operations during a growing season. In fact, the combination of mowing with the use of non-selective herbicide applications has negatively impacted desirable vegetation. These practices can be expensive due to fuel and labor hours. Due to lack of consistent vegetation management and degraded land conditions, DEN is interested in implementing a coordinated, integrated management program to sustainably manage weeds and restore highly visible DEN landscapes to more desirable conditions.

Restoring these degraded landscapes to more desirable, managed conditions can be difficult, as well as expensive. To reduce the complexity and costs associated with restoration, an adaptive land management (ALM) approach is required. In order to be successful with ALM, DEN must prioritize which areas are of greatest concern that should be managed first. To make these choices, identifying key mechanisms behind land degradation must be done. In addition, where weeds are a primary concern, managers must understand the difference between invasive and native species, as well as what kind of management strategies will help achieve desired goals for these specific areas. Controlling weed infestations when they are small and isolated is much more cost effective than waiting until they become larger problems. This part of management requires frequent monitoring and a certain level of expertise that is currently not available within the DEN operation groups.

This management plan is intended to help DEN address these issues, using a site specific, research-based approach to ALM. This plan will provide DEN with the resources and prescriptive recommendations needed to help protect and enhance the value of airport property. Recommendations will include site prioritization, effective invasive plant management techniques, desirable plant revegetation techniques to restore highly degraded sites, and follow-up monitoring strategies to maintain and protect all areas across DEN property. Adaptive land management is a process, rather than a "one size fits all" solution; therefore, management will not always be successful and continued work and alternative methods will be needed. In addition, the recommendations in this plan should be considered while developing construction and restoration specifications with companies hired for landside and airfield projects.

For any new land management recommendations, understanding the costs and benefits of adopting those practices is important. This plan will also provide DEN with cost information to assist in the decision-making process for management goals and developing field maintenance budgets for the future.

This plan is focused on vegetation management for four main landscapes located on the DEN property: 1) Pena Boulevard Transportation Corridor (PBTC) and roadsides, 2) high plains shortgrass prairies, 3) DEN airfield, and 4) agricultural land and riparian corridors. Each of these areas will be split into sections depending on the categorized land unit. Due to the large land area that makes up the DEN property, splitting management priorities into sections will allow for more site-specific strategies and relevant recommendations to smaller areas and specific systems; however, most recommendations for weed management and restoration are relevant for all landscapes and can be easily adapted.

Purpose of Plan

- Provide a detailed analysis for management options with site-specific recommendations for weeds on DEN property, with a focus on PBTC and other roadsides, shortgrass prairies, DEN airfield, and agricultural land and riparian corridors.
- Find effective management techniques, implement treatments, prioritize sites, and coordinate management activities with DEN.
- Increase knowledge and level of collaboration among DEN groups and contractors to help enhance information transfer and land management success.

- Coordinate efforts and provide DEN land managers with a more comprehensive, mutually beneficial, landscape scale land management program.

Weed Inventory for DEN Property

Successful weed management across the DEN property will require land managers to become familiar with current weed issues by understanding their biological characteristics, life cycles, and their classification under the Colorado State Noxious Weed Law. Understanding weed biology can help determine the correct timing and control method. Emphasis will be placed on weeds that are considered "noxious weeds" by the state of Colorado to meet city and county weed management requirements. To be classified as a noxious weed, the *Colorado Noxious Weed Act* states that the plant should be a non-native, aggressive invader. These weeds will often replace native vegetation, reduce agricultural productivity, cause wind and water erosion, and can pose an increased threat to communities from wildfire (CDA: Conservation Services District). While most of the weeds listed in Table 2 are considered a noxious weed, there are several other species that are not formally recognized as a noxious weed, but they are considered a "secondary weed" – plants that may be added by county petition to the level of prohibited noxious weed status (Johnson 2008). Although these weeds are not listed as noxious, effective management procedures must be taken to reduce the number of acres invaded and the adverse effects they have on these systems. Both kochia and downy brome pose threats to environments by increasing fire hazards, negatively altering desirable plant communities, and reducing the overall productivity in a wide variety of land types.

Stated by the Act, local governing agencies are responsible for managing noxious weeds on their property. Agencies include incorporated municipalities, counties, and lands owned by state and federal agencies. There are several neighboring areas that are environmentally important for wildlife sustainability, human health, and overall land conservancy; this includes the Rocky Mountain Arsenal National Wildlife Refuge and Barr Lake State Park, and several suburban communities. It is important to manage weeds to prevent spread into those areas. For more information, visit https://www.colorado.gov/pacific/agconservation/noxiousweeds or refer to the *Denver International Airport Weed Identification and Management Guide.*

Table 1 and 2 provide a list and a brief overview of the common weeds found on DEN property. These species can be found on most roadsides, in areas adjacent to agricultural land, the airfield, as well as shortgrass prairie landscapes. For more detailed information, identification for each of the weed species, and control methods, please refer to the *Denver International Airport Weed Identification and Management Guide* found in Appendix B.

Table 1. Weed species classification and life cycles. Refer to handbook in Appendix B for further information about each weed species on DEN property.

Plant Groups According to Physical Characteristics	
Grass	Monocot; single seed leaf; leaves are narrow and upright; root systems are fibrous, and they may be shallow, annual systems, or extensive, perennial systems that survive winters and spread laterally for several feet
Broadleaf	Dicot; two seed leaves; often have broad leaves with net-like vein patterns, and a coarse root system. They can be winter or summer annuals, biennials, or perennials.
Plant Groups According to Life Cycle	
Annual	Complete life cycle in one year. **Summer Annual**: Germinate in the spring, grow in the summer, and die in the fall. Control is most effective in the spring when they are seedlings. **Winter Annual**: Germinate in the fall, grow during the winter, and produce seed in the spring. Seed is produced in the spring and plant dies in the summer. Control is most effective in the fall or early spring.
Biennial	Complete life cycle in two years. Plants produce a low-growing rosette in the first year and in the second year, they produce a flower stalk. Plants will die after seeds have matured. Control is most effective in the first year.
Perennial	Persist for many growing seasons; live indefinitely. Reproduce by seed, spread vegetatively, by rhizomes, tubers, or root sections. Control can be difficult due to extensive root systems. For effective control, systemic herbicides can be used when plants are seedlings.

Table 2. Most common weed species found on DEN properties.

Weed Species	Classification	Life Cycle
kochia (*Bassia scoparia*)	Not on state weed list	Summer annual
cheatgrass or downy brome (*Bromus tectorum*)	List C Species	Winter annual
annual wheatgrass (Eremopyrum triticeum)	Not on state weed list	Winter annual
flixweed (*Descurainia hapsu*)	Not on state weed list	Summer annual
prickly lettuce (*Lactuca serriola*)	Not on state weed list	Summer annual
musk thistle (*Carduus nutans*)	List B Species	Biennial
Scotch thistle (*Onopordum acanthium*)	List B Species	Biennial
common mullein (*Verbascum 11hapsus*)	List C Species	Biennial
Canada thistle (*Cirsium arvense*)	List B Species	Perennial
Russian knapweed (*Acroptilon repens*)	List B Species	Perennial
hoary cress or white top (*Lepidium draba*)	List B Species	Perennial
curly dock (*Rumex crispus*)	Not on state weed list	Perennial
field bindweed (*Convolvulus arvensis*)	List C Species	Perennial

Ecosystem Types and Management Goals

Pena Boulevard Transportation Corridor

The highest priority area for many working groups at DEN is the Pena Boulevard Transportation Corridor (PBTC). Maintaining safe road conditions for employees and travelers is important to DEN's primary mission and vegetation provides an important element in roadside safety. Vegetation along roadsides provide soil stability by reducing wind and water erosion, provide aesthetic attributes, create safe conditions for vehicles and travelers, and reduce maintenance costs (Dudley et al. 2014). The issue is that roadsides along this corridor and secondary roads across the property are frequently disturbed by magnesium chloride applications, vehicle pull-offs, mowing operations, and numerous construction projects that bring in equipment and machinery that can introduce weed seeds and propagules. These activities cause soil degradation and compaction, spread weed seeds, and create harsh conditions that make it difficult for desirable vegetation to survive which leads to bare ground (Figure 1).

Magnesium chloride applications during the winter and early spring months often cause salt accumulation along roadsides, creating soil conditions too harsh for desirable vegetation growth (Dudley et al. 2014). Along with low annual precipitation, vegetation can struggle to survive in these harsh environmental conditions. The limited rainfall along the Front Range can cause salts to accumulate in the topsoil and are not flushed out into deeper layers of the soil and away from grass root systems. Salt accumulation can create toxic environments for desirable vegetation – and in many cases favor the establishment and persistence of weeds like kochia (*Bassia scoparia*) or can lead to bare ground in cases where no vegetation can survive (Figure 1).

Mowing frequency and heights can also create conditions that prevent perennial grasses to grow successfully. At DEN, maintaining low vegetation heights is a priority for safety and reducing wildlife hazards; however, this practice is often done during the warmer and drier months of the year, stressing native grasses that are present. Further, this alters the plant community from being a dominant grass community to a weed dominated community as they are more persistent and competitive under these conditions. For example, kochia is not only highly competitive, but it is also salt and drought tolerant, making it a successful competitor against desirable vegetation in harsher environments. Many of the invasive weed species common to the western US are well-adapted to these environments, while desirable vegetation can be susceptible and less likely to successfully compete against weeds. In addition, weeds such as kochia and downy brome, will still produce seed after mowing, further adding to next year's weed population.

As roadsides become less stable and conducive for desirable vegetation growth, they become more susceptible to erosion. Without extensive perennial grass root systems, adequate erosion and weed control are not possible (Johnson 2008). Water and wind erosion are common problems at DEN. Soil movement via water erosion causes deep gullies and large washouts that prevent successful, healthy vegetation from growing and being sustainable (Figures 2-4).

Figure 1. Eastbound Pena Boulevard roadside effected by magnesium chloride. Green vegetation is primarily kochia.

In addition, many of the common invasive weeds in this area are annuals, which complete their life cycle in a single growing season. Due to their growth habit, they have less extensive root systems, which provide minimal soil stabilization on susceptible roadsides. Therefore, it is crucial to establish healthy, perennial plant systems that will provide stabilization and safe roadsides. Pena Boulevard Transport Corridor serves as the main access road in and out of the airport, making it a high priority to many of the DEN groups involved in this project. Effectively managing PBTC will help DEN achieve its safety, economic, environmental, and aesthetic goals.

Figures 2. Grass seed has been washed away due to soil movement from water erosion. Revegetation demonstration at the 75th Ave. site.

Figure 3. Crested wheatgrass seed has been washed away due soil movement from water erosion. Revegetation demonstration at the 75th Ave. site.

Figure 4. Southbound PBTC roadside. Extreme gullies created by water runoff from the road. No vegetation, aside from kochia, due to $MgCl_2$ and water erosion.

Shortgrass Prairie

The shortgrass prairie landscapes on DEN property vary in the level of degradation as impacted by human-driven and animal disturbances. These acres are outside of the PBTC and other roadside environments. Most of the shortgrass prairie acres have been significantly altered due to weed pressure from neighboring sources (i.e. Republic Services Tower Landfill), prairie dog colonies, and historical overgrazing. Although many of the shortgrass acres have been invaded, remnant native and desirable plant populations do exist in which warm-season perennial grass species dominate. Commonly observed species include Alkali sacaton (*Sporobolus airoides*), inland saltgrass (*Distichlis stricta*), blue grama (*Bouteloua gracilis*), buffalograss (*Bouteloua dactyloides*), bottlebrush squirreltail (*Elymus elymoides*), and purple three-awn (*Aristida purpurea*). Several cool season grasses are commonly found across these landscapes as well: Western wheatgrass (*Pascopyrum smithii*), crested wheatgrass (*Agropyron cristatum*), and smooth brome (*Bromus inermis*). In addition, scarlet globemallow (*Sphaeralcea coccinea*), a forb species, is present. This list of native and desirable species can serve as a model for species that can successfully establish and persist in this environment. The present species can be used to help create seed mixes that will be more adapted to environmental conditions at DEN. Importantly, these shortgrass landscapes provide ecosystem stability and resiliency; however, when these areas are not effectively managed and experience frequent or harsh disturbances, they are less likely to maintain their stability (Chambers et al. 2014) and native grasses are less likely to survive. Downy brome poses a major threat to these areas, along with kochia, field bindweed, and several thistle species. Many of the acres that once supported a shortgrass prairie landscape have little or no remnant grass populations and are considered highly degraded. One of the drivers for weed invasion is prairie dog colonization. Current vegetation management practices, such as low mowing heights and using non-selective herbicides that kill desirable grasses, promote prairie dog colonization. These damaging colonies result in reduced native plant communities, bare ground, or broadleaf weed monocultures (i.e. field bindweed). From observations made at DEN, these colonies spread rapidly. At our research site located west of Tower Road, in a matter of eight months, prairie dog burrows moved about a quarter mile east from where the colony originally stopped in fall 2019. This spread in colonies demonstrates their ability to rapidly and negatively alter site conditions. It is important for these landscapes to continue providing essential ecosystem services and stability. In addition to managing weed populations and prairie dog colonies, increasing mowing heights to maintain healthy vegetation is crucial. Long term, adaptive management is necessary for these landscapes as they are developed for new commuting purposes and other land uses (Stantec 2019).

Agricultural Land and Riparian Corridors

Agricultural land encompasses thousands of acres around DEN's perimeter. Most of these acres are leased and managed for agricultural production. Due to the proximity to the airfield, wildlife hazard management must always be considered when producing crops and managing weeds. Under current lease agreements, tenants must use best management practices (BMPs). These include selecting crops that will not attract wildlife and managing weeds on leased acres, including the land that is under production or fallow and roadsides, around poles, and other areas where weeds occur. This strategy for constant management on leased acres is beneficial to DEN as it addresses weed control, wildlife management, and soil erosion. DEN currently requires tenants to provide USDA FSA crop reports as part of their management plan for leased acres. These reports include acres under production and yields for each crop grown; however, these reports do not address what kind of management tenants are practicing to achieve reported yields. There are useful details missing from current lease specifications that DEN can utilize to inform better management strategies on the land they manage. Changes can also be made for better documentation and communication between tenants and DEN operations. These include, but are not limited to, annual reports with weed inventories on agricultural land, location of weeds in the field relative to adjacent landscapes, and documentation of herbicides used to control specific weeds. Collecting information like this would be beneficial for DEN to better manage their own acres by developing a better weed inventory, keeping weed control records, and supporting tenants over the long term.

In addition to improved documentation and communication between DEN operations and tenants, DEN must consider the possibility of weeds moving from their managed acres into adjacent farmland, and vice versa, due to lack of weed control. This is very important for noxious weed management as it is important to eliminate the spread of these weeds into other areas. A major focus for weed control should be on roadsides, ditches, or strips of land along the perimeter of agriculture land. Each of these can act as buffers between DEN managed acres and farmland. For these areas that are adjacent to DEN managed acres, DEN will take the responsibility for management. Currently, minimal management is performed aside from occasional mowing for these areas. To help prevent weeds from spreading into farmland, or from farmland to DEN property, DEN must change current management strategies and utilize selective control to eliminate weeds from these buffers. Selective control should be the first option to contain and/or remove infestations in these buffer zones. Removing the weeds can lead to positive results, such as a release of perennial grass or a reduction in wildlife attraction near the airfield.

In addition to agricultural leased land, there are four major riparian corridors and several water collection ponds located on DEN property. The riparian corridors are considered creeks that serve as drainages for storm water management. The riparian corridors include First Creek, Second Creek, Third Creek, and Box Elder Creek. Each of these creeks and collection ponds have varying levels of degradation and weed invasion. It is important to manage these corridors and ponds in a way that maintains the drainage function and habitat stability, while minimizing the chance for weed propagules being dispersed into other areas within and outside the property. The creeks, and most ponds, are considered intermittent, in which water moves through the channels only a few times a year and the water-table is below the channel bed (EPA 2013). Although water may be present in these creeks and ponds a few times annually, ecologically important vegetation should be maintained for adequate bank and soil stabilization and overall improved habitat suitability. Due to the intermittent nature of these drainage systems, there is a lack of riparian vegetation; therefore, upland species, such as crested wheatgrass and smooth brome, are present along with several invasive species (i.e. white top, curly dock, and Canada thistle). Similar to other DEN landscapes, weeds need to be controlled around the creeks and ponds to promote healthy vegetation growth. For some areas situated in lower drainage spots where moisture persists, there is the possibility for some riparian plant species to return once weeds have been removed.

Airfield and Airport Facilities

Goals for vegetation management on the airfield are still relevant to reducing overall weed presence and maintaining healthy vegetation; however, with different regulations and restrictions compared to the land outside of the airfield, overall management goals and practices differ. The airfield is populated by perennial grasses in combination with a dominant weed spectrum, including kochia, thistle species, curly dock, and downy brome. Several grass species are consistent with those found in the shortgrass prairie landscapes (i.e. Western wheatgrass, purple three-awn); however, similar to other grass landscapes at DEN, the grass community has shifted to a more cool-season, non-native community (i.e. smooth brome). This is a result of frequent mowing and altered environmental conditions that are less favorable for warm-season, native grasses that once dominated.

Managing vegetation on the airfield is important for reducing wildlife attraction (i.e. bird strikes). The Wildlife Hazard Management Plan developed by the USDA has set height regulations on vegetation on the airfield. Current mowing heights are set at 4", which keeps grasses from producing seed, and reduces wildlife attraction; however, weeds such as kochia and downy brome are adapted to stressful conditions and can still successfully produce seed even at short heights, which may result in the opposite of the management goals for decreasing wildlife on the airfield. Therefore, managing for these two major weeds, in addition to curly dock, sunflower, and thistle species, will be important. Current vegetation management for the airfield is achieved by mowing once a year due to the vast number of acres the airfield covers. Although this method is effective at keeping vegetation heights at 4”, it does not create conditions that encourage healthy grass growth or achieve effective weed control. Selective weed control should be used in addition to mowing to reduce stress on the grasses, remove weeds that produce attractive seed, and help create sustainable grass systems on the airfield.

In addition to selective weed management, there will be areas on the airfield and around airport facilities in which bare ground (total vegetation control) is desired or necessary. Providing bare ground along runways, roadsides, fencelines, etc. will be help to increase visibility, reduce chances for fire, and reduce wildlife hazards. More information about bare ground treatments and recommendations are provided in Appendix L.

Project and Research Goals

To achieve successful land management at DEN, goals have been created between DEN and CSU. Many of these goals are relevant for all landscapes across DEN. Specific landscape goals are found under each ecosystem section.

Overarching Management Goals:

- **Provide recommendations for management and restoration techniques tailored to the invasive plant species and site conditions located on the PBTC and other roadsides, the airfield, the shortgrass prairie landscapes, as well as agricultural land and riparian corridors in which all stakeholders can utilize to accomplish successful management, preservation, and restoration**
- **Prevent further expansion by invasive weed species on all landscapes by preventing the spread of and controlling current invasive plant populations while reducing new establishment**

- **Provide education, training, and assistance to the DEN Field Maintenance team and other interested stakeholders**

Landscape Specific Management Goals:

- **Pena Boulevard:**
    - **Develop a greater understanding for the confounding factors affecting current rights-of-way along and near PBTC.**
    - **Utilize that information to create a more holistic approach for managing vegetation in addition to mowing operations, effective erosion control practices, etc.**
- **Shortgrass Prairie:**
    - **Develop a greater understanding for confounding factors affecting current shortgrass landscapes**
    - **Utilize this information to create a holistic approach for managing wildlife (i.e. prairie dogs), vegetation, mowing, etc.**
- **Agricultural land and riparian corridors:**
    - **Establish a greater understanding for current weed management practices on agricultural land while making sure Best Management Practices are being followed.**
    - **Develop tools to increase collaboration between tenants and DEN management to improve invasive plant management across land types.**

- **Airfield:**
  - **Implement new mowing and weed control strategies to promote desirable grass growth while maintaining or reducing the number of wildlife strikes on the airfield.**

Site Prioritization

Due to the size of the DEN property, it is important to be proactive in identifying and classifying areas that need immediate attention to prevent further weed spread into other areas managed by DEN and agricultural land.

1. **Mapping weed infestations and native/desirable species cover.** This is the first step in identifying priority areas. Annual surveys should be conducted to identify new or growing weed infestations. This includes rights-of-way along the PBTC and other roads, shortgrass prairie landscapes, riparian corridors, agricultural land, and the airfield. Because agricultural land is managed by tenants rather than DEN Field Maintenance, weed inventories and surveys should be required for each tenant. In addition to inventories, information about new weeds on leased acres and where they occur in the field should be provided. This information will help DEN be proactive in tracking emerging weed issues and determine if weeds are moving from farmland to DEN managed properties, and vice versa.
2. **Assess and evaluate site conditions and what species are present.** This will help determine the scale of intervention needed, management strategies required, and setting realistic expectations for DEN land managers based on site characteristics. Native plant identification can be difficult; therefore, focus on documenting specific weed species and native, desirable vegetation present.

3. **Follow the City and County of Denver and Colorado Department of Agriculture Noxious Weed Management Guidelines.** If state listed noxious weeds are present at any site, these should become a management priority. Listed species can be found in Table 1 or in the *Denver International Airport Weed Identification and Management Guide*. Managing List B species will be most important. These species should be eliminated or suppressed before seed production, depending on the species (CDA: Conservation Services District). Many of the species are widespread across the property and require control to further prevent spread. Several species are present in areas with remnant grass populations; therefore, both priorities can be addressed at the same time. For areas adjacent to agricultural leased land, DEN should utilize information provided by tenants regarding weed presence in the land they manage to identify if noxious weeds are moving from DEN managed acres into agricultural land.

Site prioritization will require a good understanding for what current conditions are across landscapes. From general surveying and monitoring on DEN property and the 40 demonstration plots established across the DEN property in fall 2019, generalized categories for site conditions have been developed to assist DEN in making restoration management decisions. It is important to understand that not all sites are identical, rather, each one will pose different challenges to reach a more sustainable, aesthetic landscape. In addition, there is high variability across the landscapes that can make classification more arbitrary. For example, there may be 2-3 acres of >50% grass cover that is invaded with downy brome and field bindweed, but 300 feet away might only have field bindweed and bare ground. Although there is variability in levels within small areas, it is important to classify the site under the condition it is most relevant (see Table 3). In the example above, the site should be classified as a Level 2 and made priority even though a Level 3 site is present within it. These smaller, challenging areas will need to be addressed accordingly.

Based off the variability that occurs across DEN, these ecosystem infestation categories should be used as general guidelines for classifying sites and can be used alongside the recommended management actions shown in Table 3 and Figure 8.

Table 3. Descriptions for different landscape types across DEN, placed into three different categories based off site conditions.

Classification/ Categorization	Site Condition Description
Level 1 **>75% cover desirable vegetation**	Sites dominated by perennial grass communities with little disturbance and invasion from weeds is considered in good condition. These areas are limited across the property but should still be managed to preserve plant diversity and stability. i.e. roadsides and open space/shortgrass prairie located north of airfield, some areas across the airfield
Level 2 **25-75% cover desirable vegetation**	Sites have remnant perennial grass communities present (Alkali sacaton, Western wheatgrass, blue grama, buffalograss); amount of perennial grass cover varies with level of natural bare ground and weed invasions from kochia, downy brome, thistle species, field bindweed, etc. i.e. roadsides located on South PBTC, open space under light rail on the north side of PBTC
Level 3 **<25% cover desirable vegetation**	Sites are bare ground (little or no vegetation growth), overtaken by prairie dog colonies, OR sites completely dominated by weeds such as kochia, downy brome, or field bindweed. Located in highly disturbed areas, close to airport facilities and highly traveled roads. Site conditions may also include effects from soil and water erosion (i.e. gullies, washouts, soil compaction, $MgCl_2$). This category may also be present within areas that are more intact.

The photos provided below give a visual representation for Levels 1 – 3 (Figures 5-7). These are not definitive for each category, as sites will have varying perennial grass and weed cover within each level; however, these should be used as a tool to help identify sites for management prioritization. Moving forward, it is recommended to prioritize invaded sites that have remnant, desirable vegetation present (Level 1 and 2). The goal for these sites is to reduce the need for further intervention once weed competition is removed and perennial grass communities have responded positively. This reduces the necessity for costly and laborious restoration efforts. Figure 8 illustrates inputs each level requires to reach a desirable landscape using a continuum scale. Some landscapes may require more inputs, or follow-up treatments, to meet goals, but this figure shows the steps and required inputs needed for each category.

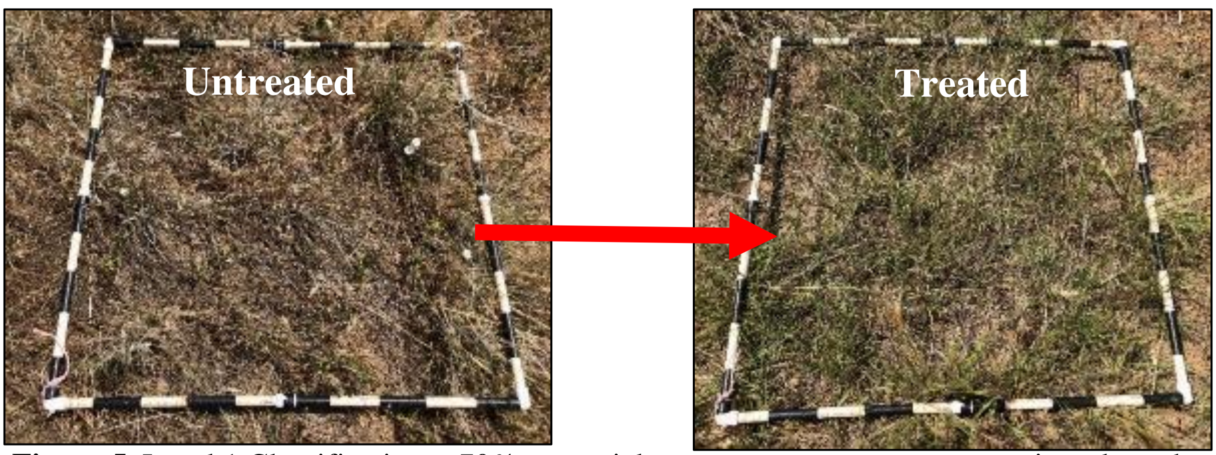


Figure 5. Level 1 Classification: >70% perennial grass; remnant grass community released after weed removal. Requires minimal inputs to achieve a successful outcome.

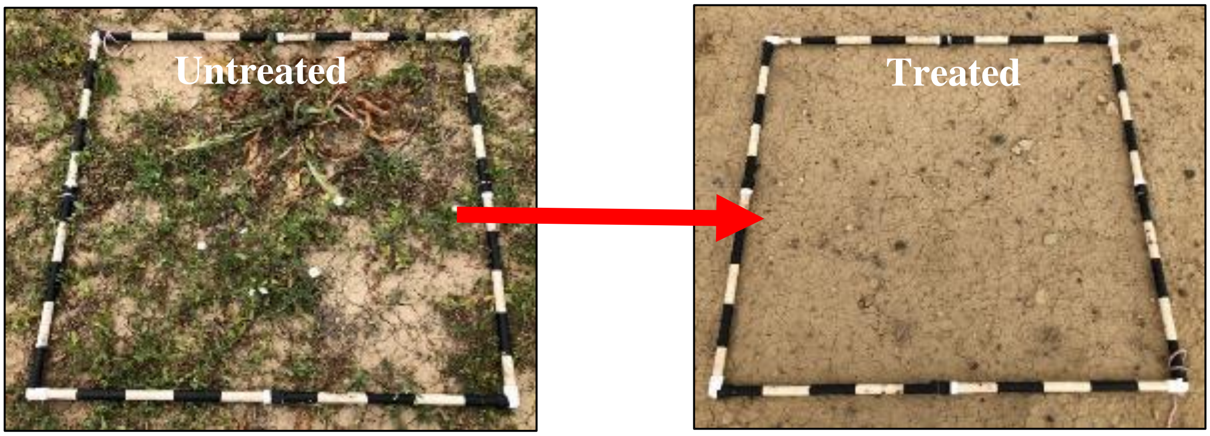
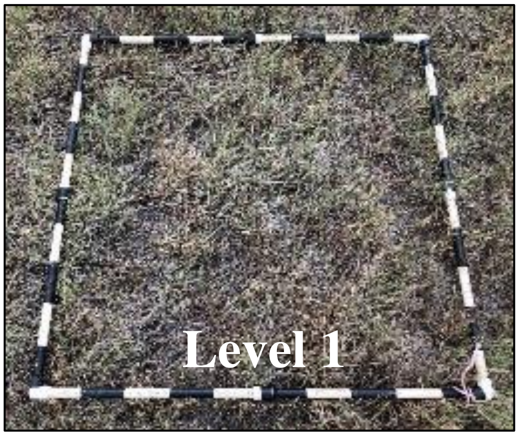


Figure 7. Level 3 Classification: <25% initial desirable vegetation; after weed control, site results in bare ground. This site is degraded and void of any remnant desirable grass community. Sites like these will require significant inputs to restore some type of desirable plant community. (Figure 8).


Figure 6. Level 2 Classification: ~50% perennial grass; remnant grass community released after weed removal. Native grass growth suppressed due to competition from downy brome.



Site dominated by perennial grass community (~70% cover) with a small downy brome infestation.

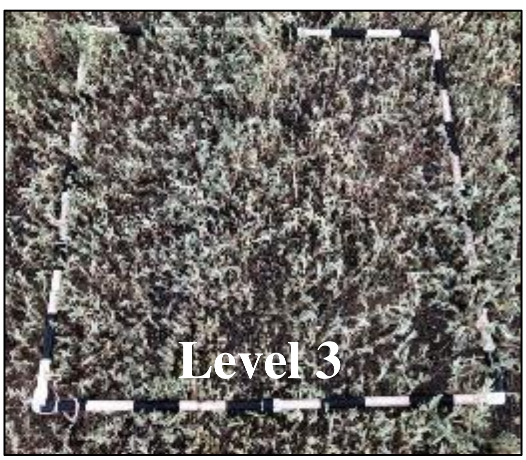
Inputs needed:

- one selective herbicide treatment to remove downy brome or other sparse weeds present
- Monitoring, 2 years after application
- Approximate cost, including application cost: $85/acre

Site dominated by downy brome and field bindweed, with ~30% perennial grass cover.

Inputs needed:

- One to three selective herbicide treatments to remove weeds from system
- Monitoring, 3 years after application
- Number of treatments will be based on the response from the desirable grasses.
- Approximate cost, including application costs: $85 to $160/acre



Monoculture of kochia, downy brome, or both, with no remnant grass community present.

Inputs needed:

- Weed control (1-2 selective herbicide treatments)
- Soil tillage/seed bed preparation
- Desirable grass introduction through drill seeding
- Monitoring, 3 years after application
- Further weed control
- Approximate cost per acre*: ~$2,100/acre (could reach or exceed this amount)

Figure 8. The amount of estimated inputs required for restoring sites based on the three infestation categories. Level 3 infestations require much more time and money to restore compared to Levels 1 and 2.

*Costs were calculated using current DEN expenses for landside revegetation projects, with the inclusion for weed management. Costs are estimated over a 3-year period. More information for the cost-breakdown can be found in Appendix K.

We recommend controlling weeds first and then evaluating the response of the desirable vegetation to decide if further management is required (Davies and Sheley 2011; Nissen 2019; Sebastian et al. 2017). Sometimes it is not necessary to introduce desirable vegetation as remnant plants will become more abundant and vigorous overtime when essential soil resources are available with no weed competition (Figure 5). The effects of controlling two of the most problematic weeds at DEN, downy brome and kochia, are illustrated in the figures provided in Appendix C. This study was done on DEN property to evaluate the response of remnant grass communities once weeds were removed from the system. In the summer of 2018, downy brome and kochia were selectively removed using herbicides and remnant grass community biomass increased five- to 10-fold after two years without weed competition. The replicated research done at DEN shows the potential for positive responses from grass communities in similar landscapes across DEN properties. If DEN were to prioritize management in Level 2 landscapes, steps toward sustainable ecosystems can be achieved with minimal inputs in a two- to three-year time frame. Additionally, for sites classified as Level 1, which are more commonly found further away from airport facilities and PBTC, are likely to still have minor downy brome and other weed invasions; therefore, it is still necessary to provide management and reduce the chance for weed expansion. A single herbicide application will likely be all that is needed to keep the desirable perennial grass communities intact.

Once sites under Level 1 and 2 have been treated, a shift towards Level 3 sites should be taken. Most of these sites will require more costs and a longer time frame (Figure 8). It is expected that revegetation and frequent weed management will be necessary to reach a healthy, reclaimed landscape. Although Level 2 sites should be prioritized first, management for both categories can be done simultaneously; however, this will depend on budgets, personnel availability, and long-term goals. For specific circumstances, such as vegetation management for construction projects (Level 3), these should be considered high priority. These sites will need frequent monitoring and management to control weeds and help grasses to establish. These responsibilities should fall under the project manager and contractor. The project manager will need to communicate management actions needed for the construction company or DEN Field Maintenance employees, depending on the contract requirements.

Pena Boulevard and Airport Facility Weed Maps

Maps are focused on the PBTC and airport facilities as these are a focus for DEN management and provide an opportunity to successfully manage problematic weeds in areas that can be easily accessible and highly visible. The PBTC and airport facilities comprise over 3,000 acres across the 12 miles from the airport main facility to south of the 40th Avenue exit. A large percentage of these acres are impacted by weeds. The PBTC was split into three separate maps with a focus on three site condition levels (Table 4). Maps contain color-coded polygons of estimated acreage to represent the three categories in areas around the PBTC and airport facilities that correspond to prioritization levels 1, 2, and 3 (Figures 9-11). This information can help inform what sites are considered a priority and further restoration efforts that are needed. These maps give a general overview for current site conditions. It is important to visit these sites and conduct further surveys using mapping systems, such as Geographic Information System (GIS) databases. This will allow for all locations of weed invasions to be recorded in one place and can be regularly updated over several years. It is recommended to visit these sites to collect information about the weed species present and determine the category these sites fall under. These maps were made using the MapItFast application provided by AgTerra Technologies.

Each of the land types described in the previous section will have varying conditions that place them into one of these three prioritization levels. Rather than focusing on how to restore and manage vegetation in each land type, it will be more important to focus on what condition they are in. Based off the defined categories in Table 4 and the associated color, these will help summarize what steps need to be taken to manage these areas. Recommendations for each level/color are provided in Appendix A.

Table 4. Description for each color that is found in the maps. Colors represent each prioritization category. Acres are focused on Pena Boulevard and airport facilities and are an estimated number.

Color	Description of highlighted sections	Acres
Blue	Level 1: >75% desirable grass cover; minimal weed infestations Downy brome, Russian knapweed, common mullein, thistle species present A single herbicide application with residual products will keep these sites intact.	232
Yellow	Level 2: 25-75% desirable grass cover; moderate to high weed infestations Mixture of weed species include, downy brome, kochia, field bindweed, thistle species, hoary cress, curly dock, Russian knapweed, and other annual broadleaf species. Remnant grass communities may be present in these areas. Estimated 2-3 herbicide applications using residual products.	1,722
Red	Level 3: <25% desirable grass cover; high weed infestations Mixture of weed species are similar to Level 2. These sites will likely result in bare ground after weed removal. These sites will require multiple herbicide applications over the long-term to keep weeds controlled. They will also require further restoration efforts, such as revegetation.	907
Total		**2,861**

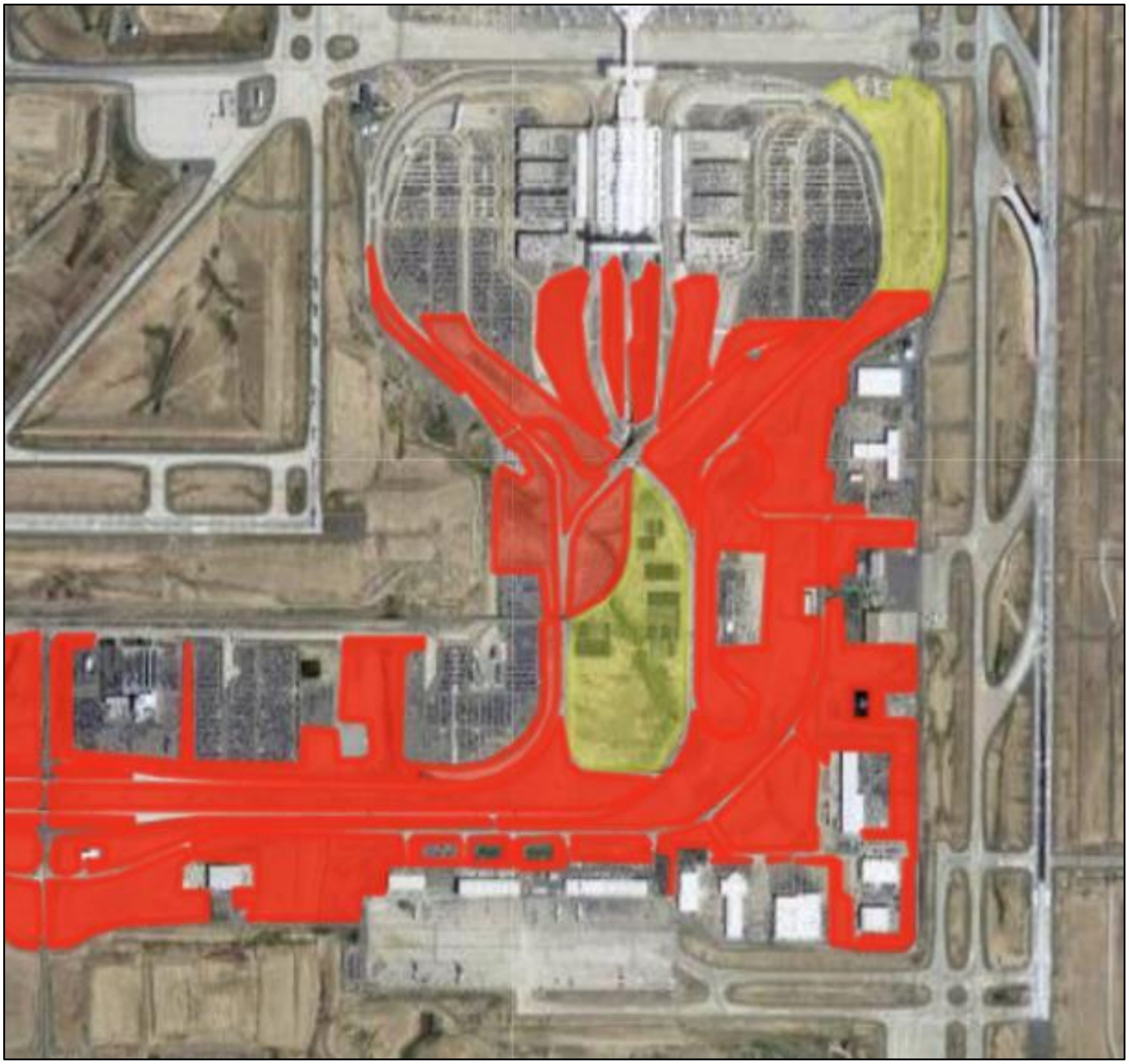


Figure 9. Airport facilities to Jackson Gap Rd. Colored polygons represent the prioritization category each area falls under. Refer to Table 4 for category descriptions and number of estimated acres associated with each.

Figure 10. Jackson Gap Rd. to Tower Road. Colored polygons represent the prioritization category each site falls under. Refer to Table 4 for category descriptions and number of estimated acres for each.

Figure 11. Tower Road to south of 40th Ave. Colored polygons represent the prioritization category each site falls under. Refer to Table 4 for category descriptions and number of estimated acres associated with each.

Weed Management Methods

Long-term success in controlling the weed spectrum at DEN involves managing the weed seed bank for each species, using control strategies at appropriate time points relative to the plant's life cycle, and using an integrated, adaptive management approach. Two important weeds at DEN, kochia and downy brome, have a very short seed life in the soil. This means that the weed seeds are only viable for one- to two-years in the soil and can be quickly removed from the system if plants are controlled before producing seed and adding to the soil seed bank. This section provides information for selective weed management and mowing practices for improving grass communities and depleting the weed seed bank. This information is recommended for rights-of-way along the PBTC and other roadsides, shortgrass prairie and riparian landscapes, the airfield, as well as reseeded construction sites.

Selective Weed Control

Selective weed control using herbicides is one of the most effective tools used to manage weeds. Herbicides provide long-term weed control, are less harmful on desirable vegetation, help improve ecosystem health, and are cost-effective. Selective herbicides control specific weed species without injuring desirable vegetation. Selective control provides desirable grasses the chance to recover and build sustainable, resilient landscapes that can prevent future weed invasions and provide soil stabilization. Many of the recommended selective herbicides provide multiple years of control with a single application, reducing labor and fuel costs overtime.

To achieve effective weed control, herbicides that are selective for the weed species need to be applied at the optimal growth stages and environmental conditions. Additionally, employees must be trained to accurately identify weeds and responsibly apply herbicides at the appropriate time.

Specific herbicide recommendations are provided in the *Denver International Airport Weed Identification and Management Handbook*[1]. This handbook provides information about specific herbicides used to target each weed species at DEN, application timings, and application rates. The recommended herbicides are labeled for use in non-crop areas, roadsides, and rights-of-way. Most recommended herbicides are selective for broadleaf weed control, excluding a few herbicides that are selective for invasive winter annual grasses. Not all herbicides are registered for use in riparian areas. Some herbicides can be applied up to water's edge, but not directly to water. The recommended treatments in Table 5 can be applied to water's edge. Precautions should be taken if there is standing or flowing water in the channel during the time of the application. Always reference and follow the instructions provided on the herbicide label when applying a herbicide.

Most of the landscapes at DEN are invaded by kochia, downy brome, field bindweed, Russian knapweed, various thistles, as well as curly dock and white top. Due to the variety of different weed species, using multiple herbicides in a single application will be the most time efficient and cost-effective control strategy. Each of the products in Table 5 provide selective, residual (pre-emergent, soil applied herbicides with long lasting soil activity) control for 2-3 years for several weed species. These herbicides can be combined with other post-emergent products to control actively growing plants.

[1] For more information about herbicide treatments, application timings, and remarks for each weed and herbicide, refer to the *Denver International Airport Weed Identification and Management Guide* and the *DEN Herbicide Application Timing Matrix*, which can be found in Appendix A and B, respectively.

Table 5. Recommended herbicide treatments for all infested acres on DEN property. See the "Considerations" section below for the addition of a post-emergent herbicide.

Herbicide Treatment	Target Species	Application Timing	Comments
Esplanade (5-7 oz) + Method (8 oz) Include 1% MSO or 0.25% NIS	downy brome, Canada thistle, musk thistle, Scotch thistle, kochia, field bindweed, Russian knapweed	Preemergence (Spring – March through June) Apply only Esplanade + Method and other selective grass herbicides (i.e. Vista) Post emergence (Fall – late-August through September) Include a post-emergence product to control growing plants (i.e. glyphosate, Plateau) If established or seeded perennial grasses are present, wait to apply with glyphosate once they are dormant	Esplanade: soil-active-targets germinating annual weeds, provides 3+ years of control for downy brome Method: broad-spectrum, 2-3 years kochia control when applied as pre-emergence
Esplanade (5-7 oz) + Method (4-8 oz) + Telar (1.5 oz) Include 1% MSO or 0.25% NIS	Same as above, plus species in the mustard family, white top, common mullein	Preemergence (Spring – March through June) See comments above Post emergence (Fall – late-August through September) See comments above	Telar: broad spectrum; include to control white top and other mustard species, and common mullein; if white top is present, best time to apply is in May when plants are flowering

Selective Weed Control Studies at DEN

Replicated studies were established at DEN to explore control options for areas with remnant perennial grass communities. All herbicide combinations provided complete downy brome control for two years (2019-2020) (Figure 12 and Figure C1). These studies at DEN and published research (Sebastian et al. 2020; Sebastian et al. 2017) support the importance of including Esplanade in every herbicide application to not only remove downy brome, but also to increase perennial grass production and overall landscape resistance to future weed invasions (Figure C2 and C3). Our replicated study clearly illustrated the impacts of downy brome on native grass cover and biomass (Tables C1-C3). Removing downy brome competition resulted in a 2- to 3-fold (2019) and 5- to 10-fold (2020) biomass increase compared to the non-treated control at both sites (Figure C2 and C3). The year-to-year variation in growing conditions was very evident at the Tower Road site. In the untreated areas, a 41% decrease in grass biomass was observed between 2019 and 2020 due to a drier spring in 2020. The control provided by Esplanade across both years and sites suggests that it is an effective tool for DEN that will reduce herbicide applications needed overtime.

Kochia populations rebounded two years after treatment (YAT). There was a 20% increase in kochia cover at both sites between the first and second year (Figure C4). Kochia will need to be treated on an annual basis, but because of its short soil seed bank life (1-2 years), it can quickly be eliminated from the seed bank after 1-2 years of consistent control with Method and other post-emergent herbicides. More information about this study and figures can be found in Appendix C. Figure 13 illustrates biennial and perennial weed control and western wheatgrass response in a large demonstration plot located along Second Creek, south of PBTC, using the recommended herbicide combinations.

Our replicated studies and large-scale demonstration plots illustrate what plant communities should fall under Level 2. Based on the response of these plant communities to simple weed management, we see these areas as high priority for management. Prioritizing DEN's land area into management categories will help make weed management goals more obtainable over time. The recommended herbicide treatments in Table 5 should provide at least 3 years of control for most weeds on the property. These herbicide combinations are designed to provide multiple years of control; therefore, a 3-year herbicide rotation is recommended. A 3-year rotation allows DEN maintenance personnel to cover a percentage of infested acres in one year, while focusing on new infested acres the next two years. Within that rotation, new acres can be treated every year. In some cases, certain sites may not need any follow-up control after the third year because the weed seed bank has been depleted from the system and the grass community has responded positively. The 3-year rotation can help optimize time and cost efficiency for controlling weeds and reaching management goals. It is important to continue monitoring treated sites because the weeds could come back in the second or third year.

For example, kochia is a prolific weed that is likely to come back in the second year when using the Esplanade (5 oz/ac) + Method (8 oz/ac) treatment. It is also likely that kochia could re-infest treated areas due to its tumbleweed behavior. Once kochia matures at the end of the summer, it will break off at the base where wind can move into other areas. This is a major mechanism for seed dispersal and infestation into other areas. The rates of each herbicide should be increased to 7 oz/ac and 10 oz/ac, respectively. In addition, follow-up applications of Vista/fluroxypyr or glyphosate (dormant season only) are recommended in the second or third year after initial treatment if weeds appear.

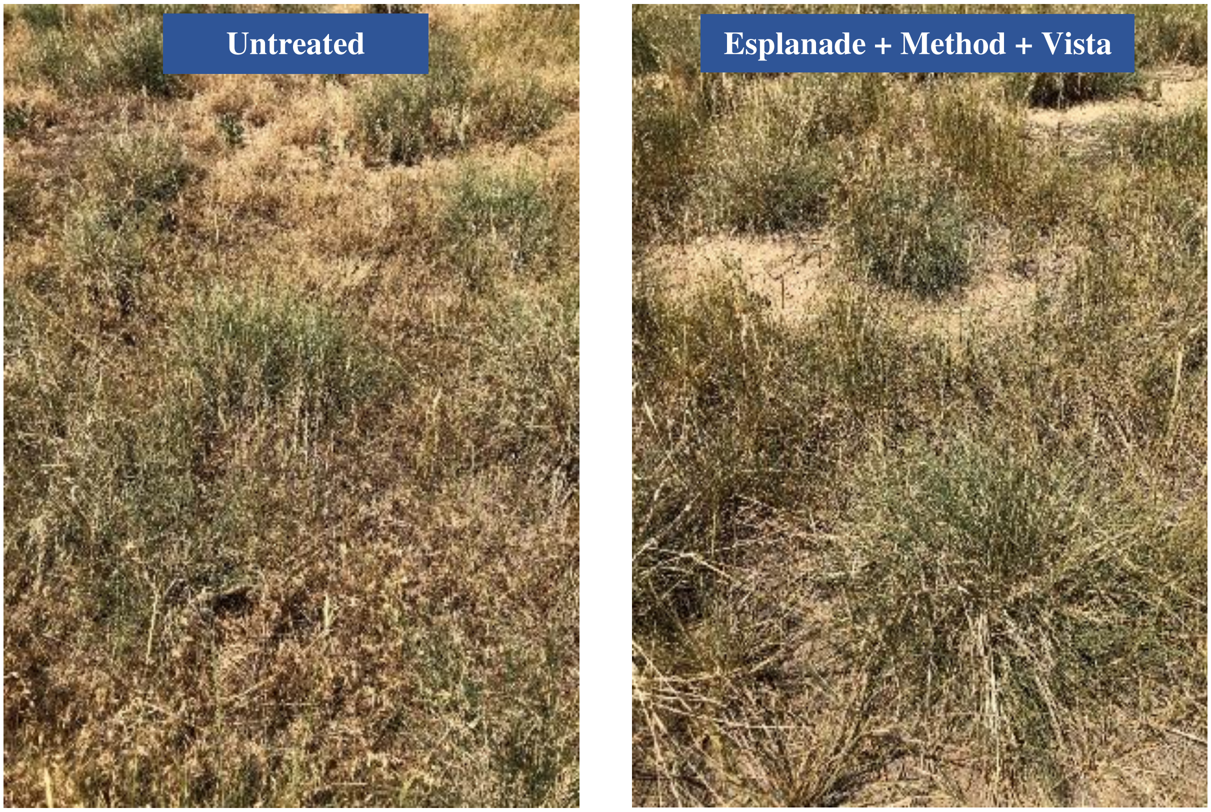


Figure 12. Grass response at the Pikes Peak site. Left is nontreated; right is treated with Esplanade + Method + Vista (2 years after treatment). Downy brome and kochia dominated this site before treatment. Alkali sacaton was released and large areas of bare ground were left after weed removal at this site. Bare ground is a characteristic of shortgrass prairie landscapes; however, these open areas can be prone to weed invasion.

Figure 13. Esplanade + Method + Telar treatment along Second Creek riparian corridor (14 months after treatment). Left strip is non-treated, right strip is treated. Weeds controlled included white top, musk thistle, Canada thistle, curly dock, downy brome, and field bindweed. Western wheatgrass was released after weed removal.

Notes for Best Management Practices using Herbicides

- These treatment options can be used in natural area/shortgrass prairie systems, roadsides, along fence lines, in rocked areas, and parking lots. Overall, these can be applied anywhere on most areas on DEN except directly to water.
- To control emerged weeds that are actively growing, include a post-emergent herbicide in addition to the recommended treatments (Table 6). This is not an exhaustive list for available herbicides; however, these were used as effective options for weed control in all our CSU sites.
- Selective herbicides, such as 2,4-D or Vista, can be used to control broadleaf weeds without injuring desirable vegetation. These options should be used in herbicide combinations

applied during the spring, summer, and early-fall months when perennial plants are not dormant. Use selective broadleaf herbicides in sites that have been recently seeded to prevent injury to seedling grasses.

- Esplanade combined with Method (selective herbicides) can be applied anytime of the year; however, when targeting downy brome, herbicide applications should be made to target germinating seeds in the soil. In the spring months, downy brome will be actively growing and since Esplanade targets germinating seeds, it will not control plants that have already emerged. Downy brome control will be provided the following year when the next generation seed crop starts to germinate. To target established downy brome plants, a post-emergent, short-term residual herbicide, such as Plateau (Table 6), can be added to applications made in the spring and fall months.
- Apply RoundUp/Makaze (glyphosate) only during the dormant months (late-fall through late-winter) in sites that have remnant perennial grasses. In late-fall/early-winter, downy brome will be germinating. Glyphosate should be included to control plants that have emerged and reduce the chance for plants to produce seed the following spring.
- Always include an adjuvant/surfactant. The type and concentration will be specified on the label. This increases herbicide absorption by improving penetration of plants' cuticle. Recommended surfactants include methylated seed oil (MSO) at 1% v/v or nonionic surfactant (NIS) at 0.25% v/v. Refer to the herbicide label for the recommended adjuvant/surfactant to add.
- Do not apply Method in areas with desirable trees and/or shrubs. Method can cause injury or plant death.

- Establish buffer zones between agricultural land and DEN managed acres to contain weed infestations. Weeds found in the invaded areas and in the buffer zones should be controlled to reduce spread into non-invaded areas. Consider using longer residual products (i.e. Esplanade and/or Method) to reduce the amount of time dedicated to these lower priority sites. A suggested distance for these buffer zones is at least 10 feet wide.
- In areas with only field bindweed, apply 8 oz of Method. Many of these sites have large prairie dog colonies, which will most likely result in bare ground after bindweed is controlled. DEN will need to evaluate further steps as it can be difficult to establish any desirable vegetation. If the decision is to keep a site bare ground, annual herbicide management will be necessary to manage the perennial bindweed and other annual weeds. For sites with desirable trees and/or shrubs, Quinclorac (Quinstar) should be used as an alternative to Method for field bindweed control. This herbicide will not injury or kill desirable vegetation and provides a year of bindweed control.
- Use Quinstar for areas that need immediate revegetation. Quinstar will not injure germinating perennial grasses. While Method should be applied in the spring, prior to seeding in the fall.
- For bare ground along fence lines, guardrails, rocked areas, parking lots, oil well and gas pads, etc. other options are available for total vegetation control. Bare ground products will provide at least one year of control for broadleaf and grass weeds, depending on the products used. A fall application is recommended to allow time for the soil applied products to be activated by winter and spring moisture before weeds germinate in the spring (Sebastian et al. 2020). One of the most effective treatments is Plainview SC. This product is a mixture of Esplanade, Method, and Imazapyr. Published research has shown this treatment provides 1-2

years of control for broadleaf and grass vegetation. The recommended application for Plainview is between 32 and 64 oz/acre. Refer to Appendix L for more information.

- Long-term monitoring will be imperative to ensure the success of restoration projects. Some projects may need more frequent adaptive management depending on the weed spectrum present. If follow-up management is necessary, rather than reapplying the same treatments to these sites, Vista (fluroxypyr), 2, 4-D, or Method might be all that is needed to control broadleaf weeds that are more likely to reinvade these sites. Herbicide combinations that can be used at DEN are not limited to this list, but other combinations can be used as well.
- Herbicide combinations are effective for controlling a broad weed spectrum. Table 7 provides a list of different combinations and estimated prices for different weed spectrums that could occur across at DEN. The weed species controlled and the estimated costs per acre are provided. Herbicide costs may vary depending on the chemical distributor.

Table 6. Post-emergent herbicide options available for actively growing weeds.

Herbicide Treatment	Weed Species Controlled	Time of Year to Apply
Vista (12 oz) (fluroxypyr) or Fluroxypyr Herbicide (12 oz)	kochia, sunflower	Spring - summer (apply when kochia is 2-6 inches tall)
2,4-D Amine (8 oz -32 oz)	flixweed, curly dock, Canada thistle, prickly lettuce	Spring - summer
Dicamba (4 oz-24 oz)	kochia, thistle species, curly dock	Spring - summer
Glyphosate/Makaze (12 oz-3 quarts)	All actively growing weeds	Late fall – late winter (desirable plants are dormant)
Plateau (7 oz) or Panoramic (7 oz) (imazapic)	downy brome – actively growing plants in the seedling stage and germinating seeds	Fall – native grass is actively growing Spring
Quinstar (12 oz) (Quinclorac)	field bindweed	Late spring to early fall – apply when field bindweed is actively growing

Table 7. Herbicide combination treatments for DEN weed spectrum and estimated cost per acre for each combination.

Herbicide Treatment	Weeds Controlled	Estimated Cost per Acre
Esplanade (7 oz) + Method (8 oz) + Vista (12 oz)	Downy brome, kochia, thistle species, Russian knapweed, field bindweed	$102.76
Esplanade (7 oz) + Method (8 oz) + Glyphosate (1 pint)	Downy brome, kochia, and all actively growing vegetation	$88.07
Esplanade (7 oz) + Method (8 oz) + Telar (1.5 oz)	Downy brome, kochia, thistle species, Russian knapweed, field bindweed, white top, common mullein	$112.93
Esplanade (7 oz) + Method (8 oz) + Plateau (7 oz)	Downy brome, kochia, thistle species, Russian knapweed, field bindweed	$92.03
2,4-D (1-2 pints) + Vista (12 oz)	Broadleaf plants – mustard species, kochia, curly dock, prickly lettuce	$20 - $22.37
Plainview SC (32 oz -64 oz)	All vegetation; bare ground/total vegetation product	$62 - $124.16

- No EPA registered herbicides contain neonicotinoids; therefore, they do not harm pollinators. It is always important to read and follow label directions for the best time to spray to avoid active pollinators. Due to the degraded nature of many DEN landscapes, there is minimal pollinator habitat because there are very few little flowering plants to provide forage (CDA: Conservation Services District ; Clark 2020; Seshadri and Sauer 2020). Simply controlling weeds like downy brome improves pollinator habitat by providing bare ground between bunch grasses that native pollinators need for nesting. If there are remnant wildflowers present, controlling kochia and downy brome has resulted in significant increases in floral resources (Clark 2020; Seshadri and Sauer 2020).

Herbicide Application Methods

Accurately applying herbicides at labeled rates is extremely important because too little herbicide will waste money due to poor weed control, while too much herbicide could injure desirable vegetation. Additionally, herbicides can be applied below the label rate, but if applications exceed the maximum labeled rate it is a violation of the law. Many infested acres at DEN will require broadcast applications using a utility terrain vehicle (UTV) or a tractor mounted, three-point hitch boom sprayer (Figure 14). DEN has pickup units designed for magnesium chloride applications that are not appropriate for herbicide applications. Slide-in, pickup truck sprayers with gas powered pumps are available. These units are priced at about $2,000. For large-scale applications, the tractor sprayer that DEN recently purchased will allow for 15 acres to be treated in less than hour, while the UTV and pickup sprayers can be used for spot treatments, roadsides, and small, or hard to reach areas. Most of the landscapes can be accessed and treated using any of these options. The UTV unit is planned to be retrofitted to make more accurate herbicide applications with boomless nozzles. The pickup unit should be equipped with a slide-in tank sprayer configuration that allows for easy application set-up. Slide-in spray unit examples are given in figures 15 and 16. These units can be found at Fairbank Equipment, Inc. in Greeley, CO. Each of these options, once properly equipped for spraying, will give DEN more flexibility in weed management and be more cost-effective than previous methods. Broadcast applications with either piece of equipment is recommended for infested sites more than half an acre, while spot applications with the hand-gun attachment on the UTV or pickup truck units should be used for smaller infestations. For smaller applications in parking lots, along fence lines, or around buildings, a backpack spray unit is an affordable and easy option. Figure 17 is an example of a backpack sprayer that is battery powered. This allows for consistent pressure to deliver the correct amount of herbicide.

Figure 14. John Deere LS1130 sprayer equipped with a 300-gallon tank and a 30-foot boom (Garvey 2017).

Figure 15. This spray unit can be positioned in the bed of the DEN trucks. It can be equipped with a boom sprayer and is currently set up for hand-gun applications with a 100-gallon tank.

Figure 16. This is another slide-in spray unit set up with a 100-gallon tank. This option is equipped with a 30-foot boom and a hand-gun sprayer.

Figure 17. Backpack sprayer powered by battery. This unit has a 4-gallon tank and can be used for smaller applications around buildings, parking lots, etc. This sprayer costs about $120.

Before applying herbicides with these units, calibration should be done to 1) determine ground speed for the desired application rate, 2) identify worn or mismatched nozzles, and 3) make pressure adjustments to fine tune the application rate. Accurate rates and uniform spray patterns are necessary to achieve consistent control. Most herbicide labels will provide information for how much product should be applied per unit area (i.e. 5 oz of product per acre). Herbicide labels will also provide recommendations for the spray volume that needs to be applied for effective coverage (i.e. tractor sprayer – 20 - 40 gallons per acre (GPA) versus handgun sprayer – 70-80 GPA). We are recommending broadcast applications made at 20 GPA.

To assist the DEN Field Maintenance team in herbicide calibration for all types of sprayers, step-by-step instructions are provided in Appendix E. Information about herbicide mixing and handling can also be found in Appendix E. Training will be required by all Field Maintenance employees who will apply herbicides on DEN property. More information about training can be found in the Employee Licensing and Certification section below. Training videos developed by DEN and CSU will be available for all employees to learn about Personal Protection Equipment (PPE) and sprayer calibration.

Recordkeeping

Maintaining a record of herbicides used on each site should be kept for at least two years. Recordkeeping will not only be necessary for the Colorado Department of Agriculture (CDA) records but will also be beneficial for the DEN Field Maintenance team. DEN employees and commercial contracted applicators will be required to keep this information. All records made by outside contractors and DEN employees should be kept together in one place. Required information includes (Colorado Department of Agriculture 2004):

- Name, license certification number, and address of who made the application and for whom it was for (i.e. John Doe, license #, Denver International Airport)
- Location of where the application was made
    - Roadside treatments should include road number, mile marker, or intersections
    - Non-crop areas away from roadsides should be fully described (GPS coordinates will be helpful)
- Target pest(s) being controlled – be specific (i.e. downy brome, Canada thistle)
- Specific herbicide(s) applied – reference the herbicide label for EPA registration number, brand name, active ingredient, and manufacturer
- Herbicide product rate – recommended rate found on herbicide label

- Application rate – the total gallons of final tank mix applied per unit area (i.e. 20 gallons per acre)
- Date and time of application

For DEN's recordkeeping purposes, these records should be used to track treated acres and weeds around the DEN property. Keeping record of where weed infestations are located and if they have been treated will be beneficial in coordinating weed control efforts among the DEN Field Maintenance team.

Employee Training, Licensing, and Certification

It is recommended by the CDA that those handling and applying pesticides be licensed to do so under the state. We recommend for at least one DEN employee have a Qualified Supervisor license (QS), and ideally two other employees operating under the QS with Certified Operator (CO) licenses. The QS license allows for the purchase and handling of restricted use pesticide (RUP), as well as the ability to evaluate pest problems, provide control recommendations, mix, load, apply pesticide, and operate spray equipment. Employees with a CO license can use restricted use pesticides without a QS present on-site (Colorado Department of Agriculture 2019). This is not a requirement for DEN, but it is highly recommended. Obtaining these licenses allows for an employee to become fully educated on pesticide use, including how pesticides effect plants, how to properly handle, mix, calibrate, and apply all pesticides. The training process and the knowledge gained are beneficial to promote safe and effective pesticide use and a better understanding on the potential for non-target impacts on desirable/native plants, animals, pollinators, and humans. Once a QS or CO license has been obtained, employees must attend workshops and seminars to earn continuing education credits to maintain their license. It is recommended that at least three DEN employees become licensed;

however, if DEN chooses to hire outside contractors for weed management, similar criteria should be required from employees within the contracted company. The QS and CO certification and licensing requirements should be included as a part of the contract agreement between DEN and weed management companies. This requirement will help DEN hire reliable, expert contractors to achieve land management goals. For more information about training and becoming licensed, visit the Colorado Department of Agriculture website.

For any employee that is required to mix, load, and apply herbicides, they will be required to complete a Non-Registered Applicator training. Employees must complete and pass the course, “Colorado Basic Pesticide Training” prepared by the Colorado Environmental Pesticide Education Program (Colorado Environmental Pesticide Education Program 2020). Upon passing this training, employees will then complete the training videos developed by DEN. These trainings will provide the necessary education and continuity within the Field Maintenance team that can help achieve successful weed management across the property.

Mowing Operations

Rights-of-way and airfield mowing are currently the single most important vegetation management strategy at DEN. Mowing is a useful tool for managing vegetation height, increasing visibility, reducing wildlife attractants, and reducing weed seed production; however, current mowing practices are damaging to roadside and airfield vegetation by reducing plant community vigor and their ability to resist weed invasions. Two of the most important practices that need to be changed are mowing heights and the time of year mowing takes place. Mowing height recommendations and timings have been adapted from the Colorado Department of Transportation (CDOT) Roadside Management and Maintenance Guide and the FAA Wildlife Hazard Management at Airports Mannual (Cleary and Dolbeer 2005; 1995) to meet state and federal requirements for roadside and airfield safety. DEN mowing practices currently do not meet CDOT guidelines specified below. In addition to unsustainable mowing practices, the number of labor hours and money dedicated to mowing is costly for DEN and provides no benefits in creating more sustainable vegetation. Based off the 2018 mowing expenses, approximately 3,379 labor hours were spent mowing. The total expense of $156,484 was solely dedicated to those labor hours, with no other inputs being covered (Brannan 2019). The vast number of hours mowing does not benefit DEN landscapes, instead they result in poor conditions that cause further degradation. The number of mowing hours can be reduced, and quality of DEN landscapes can be improved with the following recommendations. Reducing mowing needs can reduce the hours and money put towards labor and re-direct resources necessary for building a budget for weed control or management.

Landside roadsides: It is important to manage vegetation to reduce soil erosion, maintain visibility, reduce wildlife attraction, and maintain desirable plant growth while reducing invasive weeds populations. To achieve this, mowing operation timings should coordinate with desirable perennial grass and weed life cycles. Mowing high traffic roadsides (PBTC, frontage roads, and other facility access roads) should be dependent on annual precipitation, particularly during the growing season. Mowing frequency should be decreased in drier years compared to years with more precipitation; however, current roadside vegetation conditions are highly degraded and lack vigorous desirable/native plant populations to be sustainable and competitive. These conditions are partly due to mowing heights and timings that are not taking these variables into consideration.

Roadsides are often mowed during the peak growing season for grasses (May-August) and cutting heights may be too short to be sustainable, especially under drought conditions.

Mowing heights should be set no lower than the minimum recommended height of 8 inches for the PBTC (Kohlhepp et al. 1995). The time in which mowing operations take place may be the most important factor to consider. Effective mowing requires coordination with seasonal grass life cycles to prevent any reduction in the production of vital resources and essential root growth (Figure 16). To preserve present grass communities and promote future growth, aboveground biomass needs to be managed proactively.

Landside mowing recommendations: These recommendations are to support desirable vegetation growth for roadsides on landside. Apply recommendations to all relevant roadsides. The first two points should be the primary focus for developing sustainable mowing practices on the DEN landside.

- Mowing practices should be reduced to one or two annual cuttings with a focus on managing vegetation height rather than controlling weeds.
- Do not mow during the perennial grass growing season (April – September). Mowing operations should be moved to the end of the growing season (October-March) after grasses have produced and dispersed at least half the seeds to the ground(Lockman and Mount 2009). This part of the cycle is crucial for grass community regeneration for future years.
- If mowing must be done during the growing season, it is best to mow when there is adequate moisture available and plants are healthy and actively growing. Do not mow plants that are severely stressed. A chart for recommended mowing times is provided in Appendix E.
- Mowing heights should be no less than 8 inches, and whenever possible should be increased to 12 inches. This will help sustain native grass cover and provide the

opportunity for regeneration. The amount of aboveground growth removed results in a proportional reduction in root growth (Figure 18), reducing plant performance(Crider 1955). In drier years, increase mowing heights to decrease plant stress.

- Avoid mowing the entire roadside/right-of-way.
    - Reduce mowing to one or two swath widths from the edge of the roadside shoulder (6-12 feet wide). Mowing the entire right-of-way is unnecessary and can be a waste of time and resources. If mowing must be done during the growing season, consider only mowing one swath width from the roadside shoulder.
    - In some cases, greater mowing widths will be required to maintain sight distances for intersections and narrow right-of-way strips.
    - Increased spot mowing can be done as needed throughout the growing season around guardrails, delineators, etc. but prevent any mowing in areas with grass communities.

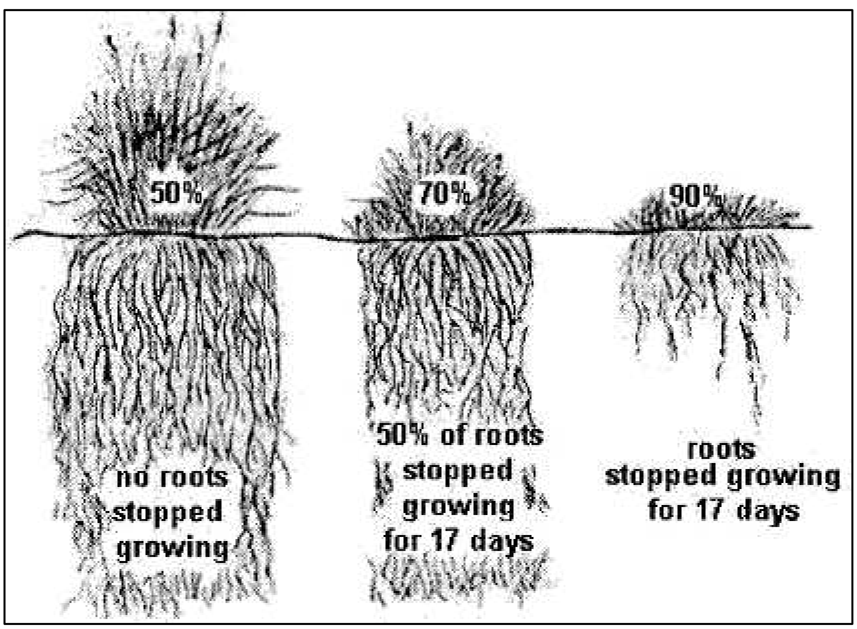


Figure 18. Belowground biomass is related to the amount of aboveground biomass present (Howery 2016).

- Do not mow immediately after or before an herbicide application. This will reduce herbicide efficacy by limiting herbicide absorption and translocation in target weeds.
- Keep from mowing once weeds have produced seed. This will disperse the seed into new areas and cause new infestations and problems. For example, mowing is often done after kochia has produced seed in mid- to late-summer. Although the size of kochia plants have been reduced, the seeds are dispersed back to the ground and into other areas. If mowing in areas with high weed density and low native, desirable grass cover, mow before weeds have flowered and produced seed.
- Mowing does not provide effective control for all weeds. For example, mowing Canada thistle or Russian knapweed patches, both perennial weeds, does not provide control. These plants spread and overwinter by their roots that are not impacted by mowing. Rather, selective control should be the main tool for managing annual, biennial, and perennial weed populations (refer to Selective Weed Control section).

Airfield mowing recommendations: Mowing is performed once a year on the airfield. Current mowing heights for airfield vegetation is set to 4 inches. In an arid environment, this creates vegetation die-offs. Due to the lack of grass cover and ability to compete, weed species have quickly replaced the limited grass cover. Alternative strategies should be considered for managing grasses on the airfield. The FAA does not have specific mowing height recommendations for airfields as they all have different environments and challenges. The USDA and DEN should consider developing solutions for customized mowing heights based off the risk levels around the airfield. The suggestions below should be considered when developing these solutions.

- Consider changing the timing of mowing operations to reduce plant stress. Time mowing to earlier or later in the growing season when temperatures are lower. Coordinate mowing with predicted precipitation events to better sustain recently cut grasses.
- Because grass heights and seed suppression must meet specific requirements throughout the year, a more feasible option might be to increase mowing heights from the current 4" recommendation. Mowing heights should be increased to 8 inches to promote healthy vegetation growth while still reducing wildlife attraction. Wildlife biologists should work closely with Field Maintenance to determine best mowing heights for encouraging grass growth and minimizing wildlife abundance.

Mowing and Weed Control: To maintain and increase grass communities in rights-of-way and on the airfield, the weeds need to be effectively managed. Current mowing practices are delayed in relation to when some of the most widespread weeds produce seed (i.e. kochia, downy brome, Scotch thistle). Also, mowing operations focused on cutting the weeds are often at the same time grasses are actively growing. As a non-selective control strategy, using mowing as the main mode for controlling weeds that produce seed mid-summer is not an effective tool for long-term management. If not done before seed production, annual weeds will have produced seed for the following year. Also, perennial species cannot be effectively controlled by mowing as they will re-sprout from their roots. Therefore, coordinating selective herbicide weed control with mowing to maintain desirable vegetation heights in rights-of-way and on the airfield should be practiced. Selective herbicides increase the ability to control these weeds throughout the growing season, while reducing the chance for perennial grass injury and stress. In Figure 19, the left picture shows a quadrat filled with downy brome and kochia, with little perennial grass. Mowing can be used to shorten these plants, but it can disperse downy brome seed to the soil and does not remove the plants from the area; however, in the right picture, selective herbicides were applied to remove downy brome and kochia, allowing for seed bank depletion. Desirable grasses present were not stressed or injured.

Figure 19. Left photo – downy brome and kochia dominate this site. Mowing does not selectively remove these weeds from the system, rather it will disperse seed, adding to the soil seed bank. Right photo – perennial grasses and bare ground. Selective herbicides were used to remove the weeds from the system, helping deplete the downy brome and kochia soil seed banks.

- For rights-of-way with desirable vegetation - mow outside peak growing season for grasses and selectively control weeds throughout the year and before annual weeds produce seed.
- For rights-of-way with no present desirable vegetation - mow during the growing season to manage heights; however, to deplete the soil seed bank selective weed control will be needed in addition to mowing in the first year after application.
- Mowing occurs only once a year on the airfield due to the number of the acres that need to be managed. Because mowing is only done once, weeds will likely outgrow grasses and produce seed. Applying recommended selective herbicide treatments once in a

growing season will ensure full season control and up to three years of residual control for some weeds, decreasing wildlife habitat on the airfield.

Chemical Mowing Alternatives

Mowing is a timely and costly method for managing vegetation heights and seed production on roadsides and the airfield. Chemical mowing is an alternative method for managing perennial grass heights and suppressing seed head production in roadsides and rights-of-way. This method is commonly used in the southern and eastern parts of the US to reduce mowing operations every year. Derigo is a product that provides effective seed-head and height suppression on a variety of different grasses (i.e. smooth brome, crested wheatgrass, and Western wheatgrass) (Sebastian 2020). With one application, grasses stay in a low-growing state for the entire season. This alternative to mechanical mowing can reduce costs, reduce damage to perennial grasses, reduce the amount of mowing each season, and minimize hazards to mower operators and vehicle traffic. With the addition of broad-spectrum herbicides like Esplanade, Method, Vista, or Telar, selective weed control and chemical mowing can also be accomplished in one application. This is an added benefit for roadside vegetation management. It is recommended to use this in rights-of-way that do have perennial grass. This alternative would also be a great option for suppressing grass height and seed production on the airfield.

A small trial was established at DEN in April 2020 to show the effects of Derigo in combination with various selective products on smooth brome and alkali sacaton. More information about this trial and other research trials using Derigo for grass height and seed head suppression can be found in Appendix G.

Landscape Restoration and Desirable Plant Revegetation

For the purpose of this management plan, restoration is defined as the process of restoring degraded sites to a productive and desirable status. Creating native or perfect conditions is not achievable at the airport due to the challenges created by frequent disturbances and less than ideal environmental conditions that have altered site conditions. Diligent and informed management will help to restore desirable plant communities, providing several benefits to DEN landscapes. Establishing sustainable vegetation on roadsides, construction sites, and open space/shortgrass prairie is a key element for land restoration and reducing weed invasion. Well-established and sustainable vegetation leads to healthier systems that require less management inputs overtime and increases ecosystem sustainability by preventing soil erosion, reducing weed re-invasion, and providing ecological benefits (Johnson 2008).

There are two types of restoration that need to be considered before making the decision to introduce desirable vegetation. There are many acres across DEN property that will require only "passive" restoration, defined as the natural recovery of a desirable plant community after weeds have been removed (Figure 20). The remnant plan community should have a threshold ground cover of $\geq$ 25% to achieve any sort of successful recovery. Site conditions should also be conducive for natural recovery. Lack of soil moisture, mowing, and weed infestations can reduce success and should all be considered when a site is going through "passive" restoration. As always, monitor these sites at least once each year to evaluate conditions and grass response. It may take several years for a site to fully recover; therefore, adaptive management will be necessary for successful recovery.

The second, and more involved restoration method, is "active" restoration. This requires several steps to make a site more favorable for establishing desirable grasses. Sites that will require re-seeding have <25% grass cover, require some level of soil stabilization for erosion control, and aesthetic goals. Landside construction projects will also require grass establishment. In this section, each step in the restoration/revegetation process will be outlined and defined, along with specific recommendations that should be considered when creating project goals.

A successful revegetation project can provide effective and long-term weed control while creating sustainable, desirable plant communities (Hobbs and Humphries 1995; Wilson et al. 2010). Perennial grasses are long-lived, highly competitive once established, and utilize resources efficiently (Herron et al. 2001). Figure 21 is a flow chart of actions that should be used when determining the steps to take in the revegetation process.

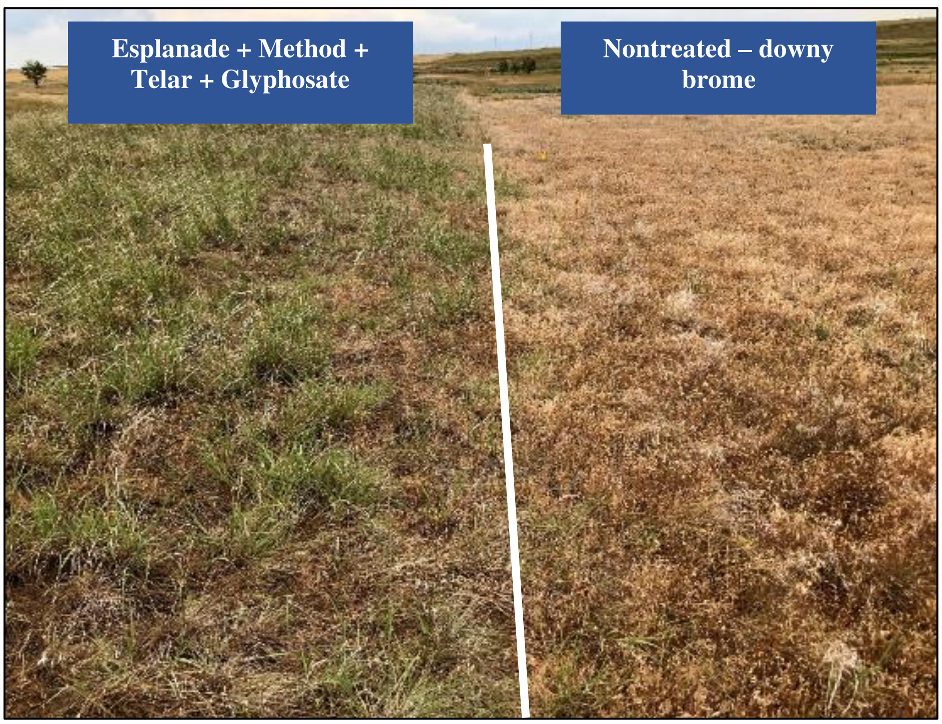


Figure 20. An example of passive recovery at a site North of Pena. Right: Nontreated control; Left: treated with Esplanade (7 oz/ac) + Method (6 oz/ac) + Telar (1 oz/ac) + Glyphosate (32 oz/ac). Applied November 2019. This site is a good candidate for "passive" restoration as the desirable vegetation cover was over 25%. One year after control, this site is going through the passive restoration process. Downy brome has been removed from the site, allowing for cool season bunchgrasses to recover and increase in cover.

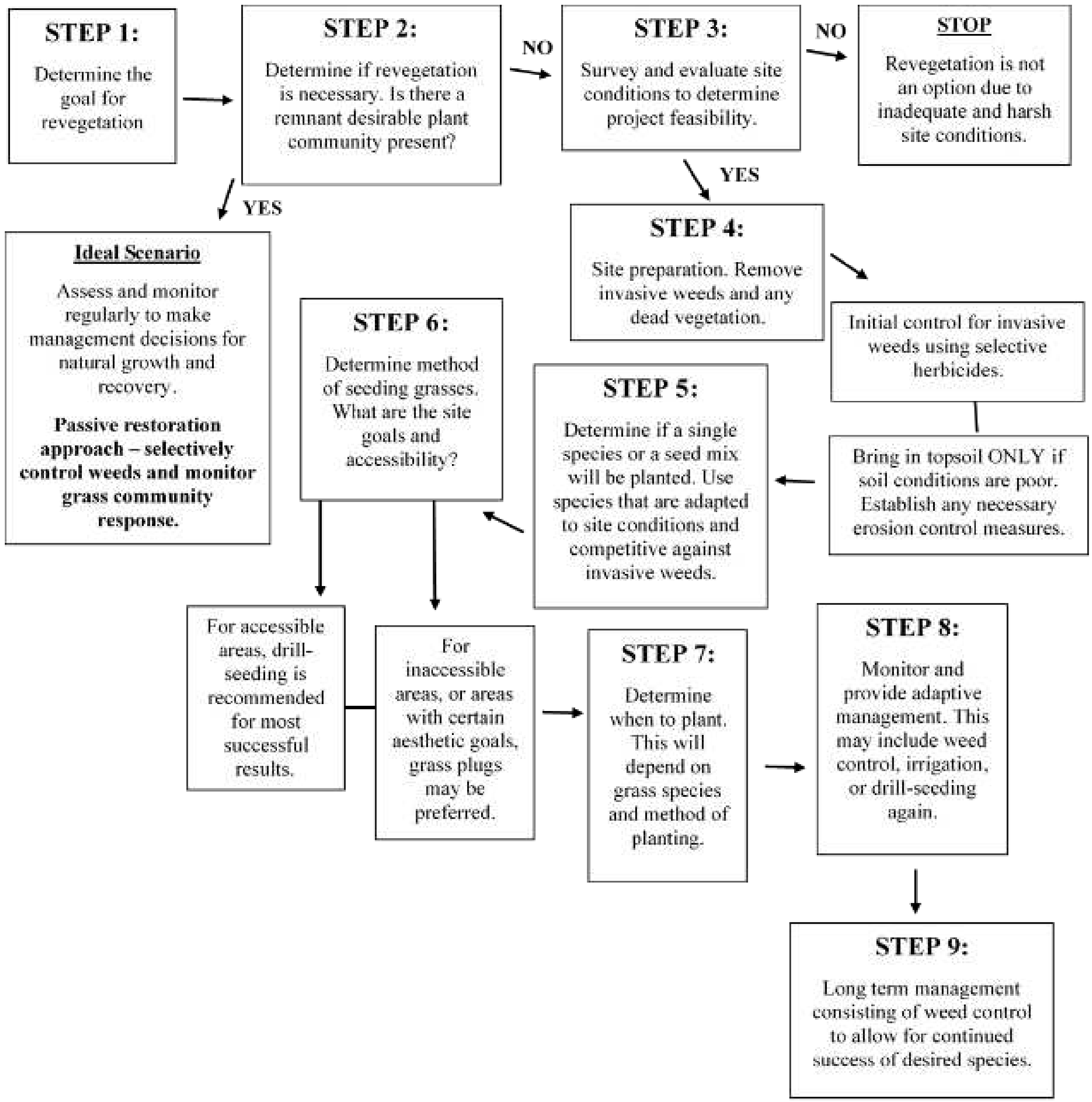


Figure 21. Flow chart for revegetating sites at DEN. For more information about each step, please refer to the same number that is listed below as is in the box from the figure.

Steps in the revegetation process:

1. Develop well-defined goals for restoration. Is it to provide erosion control, reduce weed invasions, improve landscape aesthetics, reduce overall maintenance efforts, or all the above?

2. Determine if revegetation is necessary. Are there native plant species already present at the site, or is the site void of any desirable vegetation? Consider the differences between “passive” versus “active” restoration. Revegetation work will be necessary for construction projects.
3. Evaluate site conditions and environmental surroundings to determine water drainage routes, soil conditions, existing vegetation (i.e. weeds, remnant grass communities), sun and wind exposure, mechanisms for disturbance, and the project feasibility (i.e. budget and time). Several of these conditions, such as water movement, soil salinity, compaction, soil type, hydrology, and disturbances can influence what kind of site preparation needs there are and whether revegetation is achievable. These will also influence the plant species selected for grass mixes and the potential for grass establishment after seeding.
4. Prepare site for revegetation. Preparation will depend on the site conditions determined in step 3.
    - Before seeding, weeds need to be removed from the site to allow grasses to establish without competition. Selective control for a broad spectrum of weeds can be achieved with a variety of different herbicides (RoundUp/Makaze, Vista, 2,4-D, etc.). Residual herbicides may have plant back restrictions that will require a period in which the herbicide residue can degrade in the soil before seeding to avoid negative impacts. Refer to **Desirable Grass Species Selection, Seeding and Rates** for more information about seeding after applying selective, soil-applied herbicides.

- Taking a soil test before bringing in topsoil is recommended to determine soil parameters (i.e. low organic matter, high magnesium chloride). Some sites will require the addition of topsoil; however, it is not a necessary input and does not provide any added benefit to establishing grasses. Topsoil has no regulations for physical and chemical properties. It can come from any source and be filled with contaminants or have poor soil qualities for plant growth (Darmody et al. 2009). Topsoil is an expensive cost in the revegetation process. **DEN revegetation efforts between 2014-2017 show that 60-90% of the total costs are from importing and spreading topsoil. From these project efforts, little or no success was observed when topsoil was used.** In addition, the ~1.5-inch layer of topsoil is often disked and incorporated with the soil lower in the profile. Mixing these two different soils dilutes the topsoil and can reduce any added benefits it may have had, if any.
- Soil compaction can be a major issue in the revegetation process, especially after heavy equipment operations. Using a deep tillage method (i.e. ripping) can break up compacted soil layers and increase water infiltration, allowing grass roots to easily penetrate and grow deeper into the soil profile. Disking, or shallow tillage, is another option for sites with compaction, but only targets the top 2-3 inches of the soil. Only utilize soil tillage in cases that absolutely require it.
- Erosion control in revegetated sites is not always required. For sites with steep slopes that are prone to erosion, erosion control techniques to reduce

water runoff that can create deep gullies and washout areas should be implemented. These may include sandbags placed at the top of the slope to act as a water diversion and prevent water running down the hill, erosion control blankets, or building curb and gutter systems along roads. For sites with little or no slopes, these control techniques are not necessary.

5. Select grass species that are adapted to climate and site conditions, such as precipitation, soil type, and hydrology. Given that DEN is located in semi-arid, northeastern Colorado, grass species should be drought tolerant. Salt-tolerant grasses should be included for reseeding on roadsides, as well as sites adjacent to roadsides. A single species (i.e. crested wheatgrass) may be the most successful grass species to establish in these harsh conditions. If a seed mix is desired, include 5-6 different species in a mixture. Adjust seed mixes to match site conditions. More information and research about successful grass establishment at DEN is provided in the **Selecting Desirable Grass Species and Seeding Rates** section.
6. Determine planting method depending on the site accessibility.
    - Drill-seeding is preferred for revegetation as compared to broadcast seeding. Drill-seeding places the seed beneath the soil layer, protecting it from wind and water erosion and wildlife. Use a no-till rangeland drill to plant seeds on flat terrain and on low to moderate slopes (Figure 22). The ideal planting depth is species dependent, generally dependent on seed size. The smaller the seed, the shallower the planting depth. Most rangeland drills will control seeding depths using depth bands which will allow for planting depths between 0.5 to 0.75 inches deep. Press wheels

should be used to improve soil to seed contact. Compared to broadcast seeding, drill seeding will significantly increase the odds for successful grass establishment success (Nelson et al. 1970; Nissen 2019; Pyke et al. 2013).

- DEN has many acres that can be seeded outside of landside construction revegetation projects, purchasing or renting a rangeland drill for in-house seeding work should be considered. In addition, DEN should consider using their own rangeland drill and purchased seed to seed construction projects. DEN maintenance personnel can seed these areas, which allows for consistency and saves money by not hiring outside contractors (Appendix J).
- The Truax FLXII in Figure 22 or a Truax On-the-Go (OTG) in Figure 23 are rangeland drills with three seed boxes that provide different seed types to be planted (large seeds i.e. wheatgrasses; fluffy seeds i.e. sideoats grama; and small seeds i.e. inland saltgrass). They require no tillage before planting and can be easily calibrated for seeding at specific rates. The Truax FLXII costs approximately \$20,000-\$30,000 and the OTG costs approximately \$42,000-\$38,000 depending on the size of drill (Truax Company Inc.).

Figure 22. A Truax FLEXII no-till rangeland drill. There are eight drill rows on this planter, but they range from 6-22 rows depending on the unit purchased. This drill was used for the CSU revegetation plots at DEN.

Figure 23. Truax OTG rangeland drill is another option for DEN to utilize for in-house seeding work. The number of drill rows range from 8-22.

- If broadcast seeding is the only option, till the soil to provide a rough surface, broadcast seed, and then improve soil-seed contact by compacting the soil using a culti-packer (heavy metal roller with protrusions that push the seed into the soil) (Nissen 2019).This method requires more equipment, twice the amount of seed per acre compared to drill-seeding, and has a lower chance of success than drill seeding, and results in increased soil disturbance.

- Hydroseeding should be used for sites with steep slopes or sites that are inaccessible. Hydroseeding seeding is a mixture of seed and mulch that provides erosion control and increases the likelihood for seeds to stay in place on slopes that are prone to water erosion. This seeding method is often done on construction sites and is recommended that it be restricted to only construction sites that are not easily accessible.
- Container grown plugs is another revegetation technique often done for smaller sites, or sites with steep slopes. Planting mature grasses in the landscape can increase the chances for establishment when compared to broadcast or hydroseeding. Plugging is recommended for areas with steep gradients, rough terrain, have specific aesthetic goals that cannot be achieved with other forms of revegetation, or a relatively small area. It is more expensive and labor intensive than most seeding options.

  Grass plugs are started from seed in a greenhouse and should produce several tillers before they are ready to be transplanted into the landscape. Plugging should be done before roots become rootbound in containers as this can prevent it from spreading and surviving in the landscape. CSU utilized this revegetation technique at two different sites, in addition to a GeoWeb demonstration site.

Appendix G describes the process and observations from using this method in two different landscapes with different project goals.

- At both revegetation research sites, plugging was done to determine the establishment and persistence success. The decision to use grass plugs will depend on site goals; however, it is not the preferred option for large areas with little or no slopes that can be easily drill-seeded.
- For any sites with steep slopes or areas prone to erosion, a mulch or erosion blanket will be necessary to reduce soil and seed movement and increase chances for grass establishment. If mulch is used, make sure that it is certified as weed-free, whether it be straw or hay. Erosion blankets or mats may be preferred over mulch as they will not have this issue and have a greater likelihood of staying in place once installed. If erosion blankets are used, biodegradable types are preferred. The Earthwork Construction Requirements for erosion control (Sections 213 and 216) should be referenced (Colorado Department of Transportation 2019). Immediately after seeding a site, the mulch or blanket/mat should be applied. For sites with little or no slopes, these erosion control techniques will not always be necessary.
- Most desirable/native grasses that are adapted to DEN environments do not need extra fertilization (i.e. nitrogen) except under very unusual circumstances. Fertilization is more likely to promote weed growth and competition (Darris 2003) rather than promote the growth of seeded

grasses; therefore, it is not recommended to add fertilizer in revegetation sites.

7. Establishing perennial grass is dependent on environmental and climatic conditions. Cool-season grasses should be planted before the ground freezes in the fall (October to early-December), as a dormant season planting. Cool-season grasses require a cold stratification period to be able to germinate the following spring once soil temperatures reach ~55 F. Spring seeding is possible for warm-season grasses, but precipitation can be more variable and supplemental irrigation will be necessary for establishment. Research done by CSU at DEN and other locations across the Front Range have shown both cool- and warm-season grasses planted in the fall establish successfully under normal growing conditions. Colorado's Front Range receives a significant percentage of its total annual precipitation during winter and early spring, while summer months are generally hot and dry. The process which has provided the most consistent perennial grass establishment is to 1) start controlling weeds in the spring to keep sites weed free through the summer, 2) plant desirable grasses in the fall, and 3) conduct adaptive management throughout the establishment year. Controlling weeds the year before grass planting allows for any precipitation to replenish the soil profile, much like the wheat/fallow system used by Colorado producers. This process will increase the potential for success, especially in dry years like 2020.
8. Monitoring and adaptive management should be done for at least two years following seeding. Significant grass germination may not take place until the second year after seeding; therefore, monitoring and management is necessary for controlling weeds and assessing grass establishment. Although weed control will likely be the most important

step in adaptive management, other important factors that will determine success include, wildlife management, water and soil erosion, and moisture availability. In order to manage weeds, there are selective, non-residual herbicides available that can be used safely on seedling grasses to reduce competition from annual broadleaf weeds in early revegetation stages. Spot spraying of more persistent weeds may be necessary. Providing at least two years of weed control while grasses are establishing is imperative for their success. Construction projects that have been revegetated are prone to annual weed invasion after a major disturbance (Figures 25). Thus, they need to be proactively assessed for infestation and grass establishment. Appendix J provides an example for the necessity of doing adaptive management and illustrates what happens when timely adaptive management is not provided (i.e. Fire Station 35). Kochia and downy brome quickly invaded the recently seeded site and weed control was not provided until after the weeds were too big to effectively control; however, once weeds were controlled, slender wheatgrass successfully established in most areas at the site.

In addition to regular monitoring at revegetation sites, monitoring and adaptive management should also be done for at least two years at sites where weeds were removed, and desirable plant communities already exist. There are several methods available to collect information and for tracking project success. DEN should utilize simple, yet useful tools to help monitor these projects.

- Visual assessments are simple and can be made early in the growing season (mid- to late-spring) to determine grass establishment and weed presence. Visual assessments may be required more than once during a growing season to survey weeds as they germinate over the course of several months and to inform proper control strategies. We recommend monitoring sites at least twice during a growing season.

- Photo point-monitoring - Photographs provide a visual record of changes occurring to plant communities during the restoration process. Points at which photographs are taken at should be geographically referenced, or physical markers should be made at the site, to return to each year. This information will help evaluate how restoration efforts are progressing and document improvement, degradation, or no change (Department 2016). After 1-2 years of monitoring, further mitigation can be necessary depending on the response from restoration efforts. The **GrassSnap** app is a tool that utilizes this monitoring method to meet restoration goals. All photo points can be stored in this app for ease of data collection and storage. For more information about this app, visit https://extension.unl.edu/statewide/centralsandhills/grasssnap/.
- In addition to visual assessments using photos, observations should be recorded to compare the infestation size before weed control and seeding were done to the response after a growing season. Use both forms of record keeping to determine if management methods are helping reach project goals. Keep records on treatments applied, weeds controlled, infestation size before and after treatment, number of established grasses per unit area, etc.

Figure 24. Fire Station 35 after a revegetation project. In spring 2020, downy brome, kochia, and other annual broadleaf weeds invaded the site. Two Vista applications were applied to control the kochia and frequent monitoring was done throughout the growing season. Slender wheatgrass established later in the season once weeds were effectively controlled.

- As noted in step 7, stored soil moisture and timely precipitation are key for grass establishment. To increase successful establishment in years with low precipitation (<10 inches annual precipitation), supplemental irrigation may be necessary. Where irrigation is feasible, it is highly recommended for the first 1-2 years.
    - In the first year after seeding, once temperatures get warmer (early or mid-May), temporary irrigation should be provided until grasses are established with 2-3 tillers. More frequent watering should be provided earlier in the growing season and tapered off later in the summer if grasses are established. If there is adequate natural precipitation, irrigation may not be needed every week. In the second year, once grasses are established, irrigation will only be necessary for a couple of months.

Irrigating in late-May through June should provide a good amount of moisture for established grasses to get through the summer. In dry years, such as 2020, grasses may need to be watered 1-2 times in the late summer.

- Temporary and affordable options for irrigation systems are available. A simple system was designed for the DEN seeding demonstration plots. This system can be adjusted for small and large sites. Another example of this kind of system was used for the reseeding project at Fire Station 35.
- **Temporary Irrigation System:** nine sprinkler heads attached to 250-foot long PVC pipe; sprinkler heads spray up to 70 feet and rotate 360°. Sprinkler heads were spaced along the PVC pipe every 30 feet. At 125 feet along the PVC pipe, a ¾" hose connection was made to be hook up to a 3000-gallon water truck. One 3000-gallon truck delivers ~1/2" of water to 12,500 ft^2 area. Figure 25 illustrates the sprinkler system. This system was configured specifically for the demonstration sites. The idea from this system can be easily adopted to be used in other areas. **Ken Martinez** from the Field Maintenance team helped in building the sprinkler system and is a useful resource for similar future projects.

If seeding and significant vegetative cover is necessary for closing construction contracts, a version of these recommendations should be included in the contract specifications to provide requirements for revegetating project sites. For example, current DEN contracts state that vegetative cover must be at least 70 percent of pre-disturbance levels(Colorado Department of Transportation 2019); however, this does not specify what kind of vegetation or the timeline in which this plant density level needs to be reached. Weeds tend to dominate recently disturbed sites and are considered acceptable cover by DEN. Therefore, erosion control and revegetation requirements in

Figure 25. Simple irrigation system used to ensure grass establishment at DEN demonstration sites. Left picture – hose connection located at the middle point of the 250 ft PVC pipe. Right picture – PVC pipe runs down the middle of the site.

contracts need to be more specific. A recommendation is to clarify that vegetative cover must consist of tillered grasses after seeding and a specific timeline in which final stabilization should be reached.

In addition, at least two years of adaptive weed management should be provided in a contract. Weed management should include monitoring and treating weeds in the area, as needed. Once a contract has been closed, continued long-term monitoring by DEN will be necessary for reseeding success.

It is important to understand that seeding efforts can fail after going through this process. The grass response is unpredictable and is dependent on several factors. Due to grass establishment being so dependent on moisture, in years with below average rainfall, grass establishment will be difficult. If grasses are established, it can still be difficult for them to persist in very dry years when they are 1-2 years old; therefore, it will be vital to provide weed control for these sites.

When managing such a large and diverse property such as DEN, it will require expertise in weed management, plant ecology, and restoration. It will also require planning and organizing, in which a timeline is provided to allow for a better visualization for when tasks need to be completed across the year (Figure 26). Hiring a specialist in plant ecology, weed management, and/or land restoration will be vital for land management success at DEN. An employee dedicated to this area of land management will help increase effective collaboration with the field maintenance, landside engineering, real estate and sustainability groups. In addition, this position should work closely with construction project managers to make effective and proactive management and restoration decisions regarding reseeding projects.

Creating an annual management action plan based on this timeline will help prioritize the activities needed to accomplish land restoration. Several of the activities overlap, therefore, these tasks will need to be allocated to designated field maintenance employees should DEN decide to manage weeds and undertake revegetation efforts. If contractors are brought in to do this work, a similar timeline should be included in future contracts.

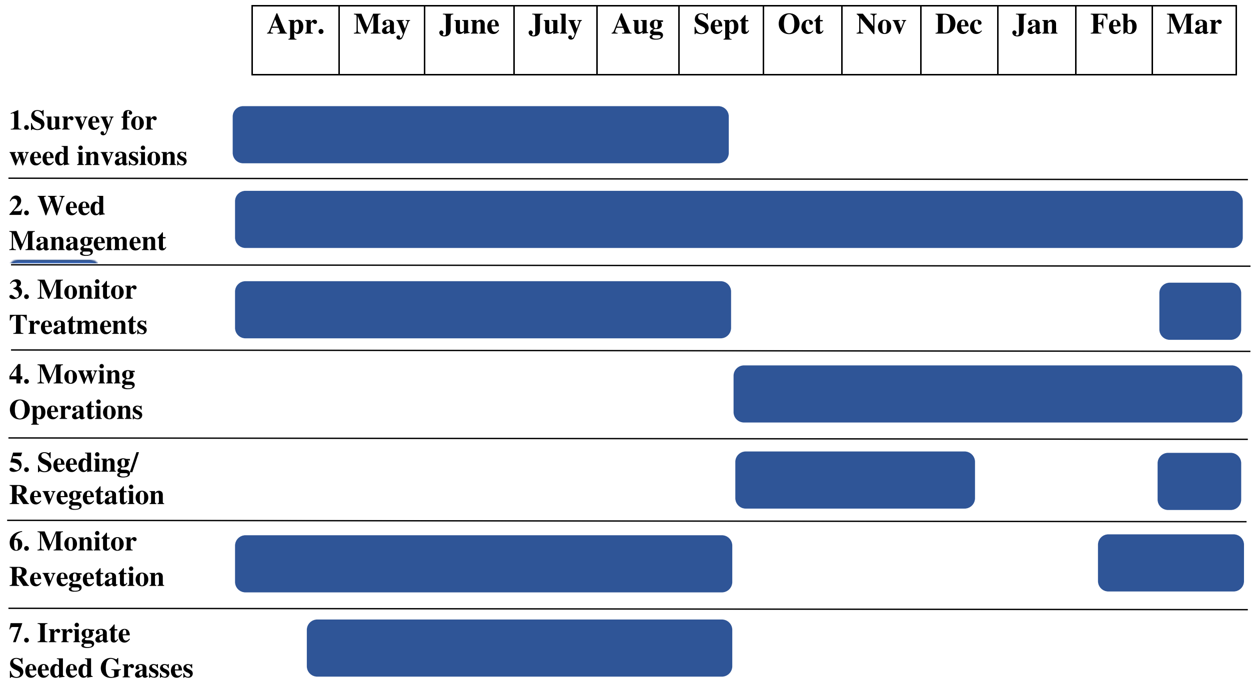


Figure 26. Management timeline of actions that should be performed throughout the year. Each box indicates the time in which each action should be done for best results.

Management timeline actions:

1. Survey weeds during the late-spring and summer months when plants are actively growing and flowering. Species identification is easier during this period.
2. Herbicide applications can be done throughout the year to control multiple weed species. Refer to the Herbicide Matrix and the handbook (Appendix B and C) to determine the timing and treatment for each species. Herbicides are more effective at certain points in a plant's life cycle. For best results, refer to the resources above to find the best timing for each species.
3. When reseeding a site, weeds should be controlled in the spring to allow for a vegetation-free period in which moisture can build up in the soil before seeding. Therefore, a spray schedule should be outlined to control weeds the season before seeding and for the next spring once grasses have germinated.

4. If necessary, seeding can be done in the early spring once soil temperatures reach 45 F. Supplemental irrigation throughout the spring and summer will be necessary to help grasses establish.

Selecting Desirable Grass Species and Seeding Rates

1. **Selecting suitable grass species** will depend on site conditions, project goals, and available resources.
   - Before selecting grass species, soil testing should be performed to determine soil texture, organic matter, and salt content. Selected species should be adapted to an arid environment. Although there are resources (Darris 2003) that recommend using reference species, or species that are found in similar conditions across an area, this might not be a feasible option for DEN in every situation. Striving for a native perennial grass system for construction sites and other areas that have been heavily disturbed may not be achievable. From seeding demonstrations done at DEN, grass establishment for several native grasses (i.e. alkali sacaton, green needlegrass, western wheatgrass, slender wheatgrass, inland saltgrass) was not successful in the first year due to no moisture. These seeded sites have been altered through soil movement from past construction, water erosion, weed invasion, $MgCl_2$ applications, etc. These harsher conditions are not ideal for native shortgrass species and make it very difficult for them to successfully establish. Therefore, it is important for DEN to find species that are good establishers and persistent; however, these species will likely not be native as most introduced grasses are the most adapted to these conditions. These species need to be salt and drought tolerant, as well as rapid

establishers and persistent to provide timely soil stabilization. Additionally, grass species should be minimally attractive to wildlife to reduce hazards.

- The choice between using a seed mix or a single species (monotypic stand) will depend on the site goals, site variability, and project scale. While seed mixes can be beneficial for providing ecosystem stability through a diverse plant community, monotypic stands can be easier to establish and manage.

Monotypic grass stands: For sites with harsh conditions where establishing desirable grasses will be difficult, a monotypic stand of crested wheatgrass may be a logical option as it is well-adapted to these conditions. Studies across the western US have shown that crested wheatgrass is a desirable perennial that establishes quickly, persists for several decades under a wide range of environments, and is competitive against weeds(Cox and Anderson 2004; Robins et al. 2013). In addition, our site-specific research at DEN demonstrated that the "Ephriam" crested wheatgrass had the greatest potential for establishment. We compared crested wheatgrass, inland saltgrass, alkaligrass, and manystem wildrye and found that crested wheatgrass had a stand frequency of 83%, compared to 44% for manystem wildrye, and 0% frequency for the other two species. Frequency is the presence or absence of a plant in a sampling unit, which was converted to a percentage (Vogel and Masters 2001). Figure 27 shows a frequency grid made of a metal frame (~1 m^2) with 25 squares that was used as the sampling unit. The number of squares with one or more plants were counted. In this example, crested wheatgrass was present in all the squares, except for two. This process was repeated three more times across the plot to reach a total of 100 squares. The total number of squares where plants occurred were divided by 100 to calculate the percentage for stand frequency. Figure 28 represents a stand of well-established, low growing crested wheatgrass at one of the seeding sites. On severely degraded sites with low precipitation, using a persistent grass like crested wheatgrass is a reasonable option. Especially if the goal for a site is to provide erosion control and weed competition.

Figure 27. Frequency grid with 25 squares. The total unit size is ~1m^2. The number of squares with one or more seeded plants is counted. This was repeated three more times and the total number of squares with plants was converted to a percentage by dividing by 100.

Figure 28. Vigorous crested wheatgrass stand at the 75th Avenue site was seeded in Fall 2018, and is now well-established.

Seed mixes: A multiple species seed mix does have advantages. Mixtures offer a more diverse and an aesthetically pleasing landscape that provides beneficial aspects for controlling erosion and creating sustainable grass ecosystems. Grass mixes should be simple, with 5-6 species, or less, and targeted toward the specific soil, hydrology, and habitat at the site. Recommended seed mixes and seeding rates are provided in Appendix H.

- Mixes should include at least one fast-growing, short-lived species, such as slender wheatgrass, to provide rapid cover and short-term stabilization. This provides time for the slower growing, more persistent species to become well-established in the first 2-3 years. The fast-growing species should not make up more than 15% of the seed mix, while the longer-lived species make up the rest of the mix. For most upland sites, a single seed mixture can be used. A single mix allows for species to thrive in certain microhabitats across large areas and reduces the complexity in re-creating desirable landscapes (Darris 2003). To account for the variety of different site conditions found at DEN, five upland seed mix options are provided in Appendix H (i.e. Saline-Upland vs. Saline-Swale/Bottomland). A single seed mixture is provided for drainage sites that experience inundation several times during the year. This mixture is designed with species that have upland characteristics, but also characteristics adapted for soils that experience minor inundations.

    - These grass mixes should only be planted in sites that have adequate moisture or that can be supplemented with irrigation. The mixes are composed of only native species; therefore, establishment and persistence will likely be unsuccessful in sites with little moisture and poor soil conditions. If these mixes are used, it is suggested to use them for sites that do not require quick establishment for roadside stability. More time and effort will be necessary to get these established compared to a monoculture of crested wheatgrass. Establishment may take longer, thus more weed control and irrigation will be necessary during this process.

- For many seeding projects, grass establishment may not occur the first year after seeding. Ideal conditions for grass establishment will likely not occur the first season after planting. This could be due to low precipitation in the fall/winter or soil conditions, for instance. Therefore, seeding should not be considered a failure until after the second or third season. Seeding trials at DEN, as well as others across the western US, have seen that significant germination and growth often occurs in the second year after seeding. During this time, weed control will be necessary to keep sites weed free to give the seedlings a chance to establish. Seeding failures are common, if no grass establishment occurs 2-3 years after seeding, consider re-seeding the site again with a similar seed mix or a monotypic stand of crested wheatgrass. Site conditions may need to be re-assessed and altered to make conditions more suitable for grass establishment.

- Until seeded grasses have established and persisted for 2 or more years, native perennial forb seeding, or shrub plantings should not be done due to unpredictable results from poor establishment. Recommended rates for forbs in DEN seed mixes are below 0.5 pounds of live seed (PLS) per acre. When added at such low rates and due to the nature of these species, they are easily outcompeted by perennial grasses in the same mix. If project objectives do include forb species to improve biodiversity and ecosystem sustainability, a long-term plan would need to include seeding forb species three to four years after desirable grasses have established and annual weed pressure is low. At DEN, grass-dominated systems would be best supported on these landscapes and should be the main goal for next 5-10 years before considering introducing forbs.

Established grasses are susceptible to herbivory (Figure 29). Monitoring grass stands will be important to evaluate whether wildlife, such as rabbits, are adversely impacting grasses. In very severe cases, it might be necessary to build barriers around seeded areas to keep wildlife out of these areas and allow for grasses to grow.

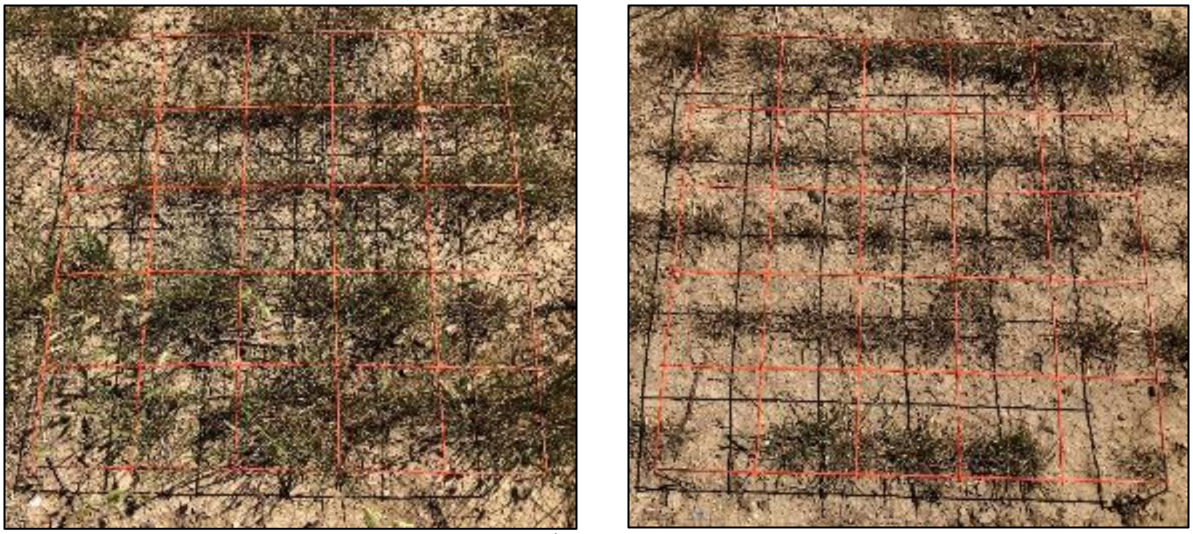


Figure 29. Rabbit herbivory at the East 75th Ave. site. Healthy crested wheatgrass stand on the left; rabbit impacts on the right. Under severe environmental conditions this type of stress could impact grass persistence.

2. **Seeding and weed control:**

- As previously mentioned, adaptive weed management is critical throughout the revegetation process. Weed control should be done in the spring and summer before seeding in the fall and for at least two seasons after seeding to give grasses the chance to fully establish. Establishment success will be highly dependent on weed control and timely rainfall or irrigation.
- Select herbicides with no soil residual activity for applications made before seeding and during the establishment year. Some pre-emergent and post-emergent herbicides can prevent grasses from germinating and cause injury to young seedlings. In the initial phase before seeding and in the early stages of grass establishment, it is

recommended to use short-term or non-residual herbicides for weed control. Products include glyphosate (pre-plant or dormant use only), 2,4-D, dicamba, and Vista.

- Herbicides with no soil residual activity can be used to control weeds until the point that grasses are seeded and after planting, but before seedlings emerge.
- For revegetation projects, products with long soil residual should not be used until later in the restoration process due to the risk of injuring or killing seeded grasses. For example, Esplanade could prevent grasses from germinating if applied before planting, and Method could injure grass seedlings before they are established. It is recommended to apply these products once the grasses have several tillers (Figure 30) and are well-established. This could be after the first growing season, or in the second year depending on annual precipitation and other environmental factors.

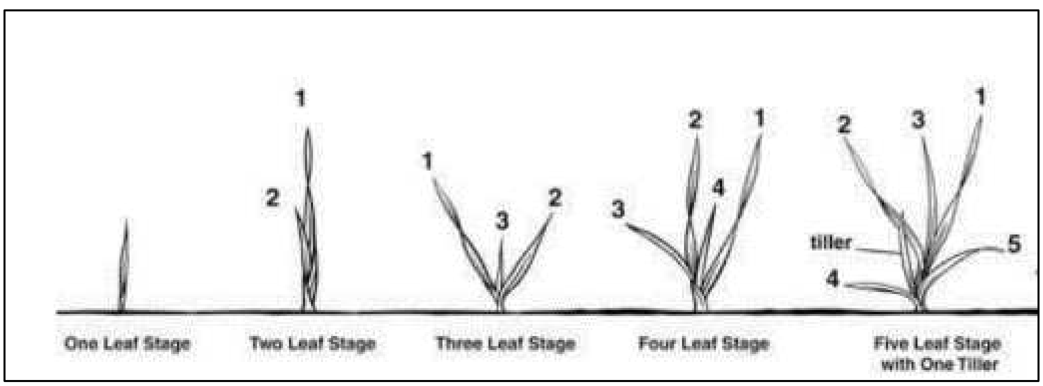


Figure 30. Diagram for the early stages of grass growth. Once grasses reach the 4th leaf or tiller stage, they are stronger and better able to tolerate herbicide applications(2014).

- At the two revegetation sites at DEN, seasonal weed control was done in spring 2019 and 2020 to remove weed competition that could hinder seedling growth in the establishment process. Non-residual products were used in the first year since grasses were in the seedling stage or had not germinated yet. In the second year, we did include a residual product (Escort – metsulfuron) since the grasses were larger and well-established two years after seeding. Proactive management resulted in acceptable weed control for both growing seasons.

The seeding project at Fire Station 35 is an example of what not to do when it comes to controlling weeds in the process of grass establishment. Kochia was the primary weed at this site along with downy brome, prickly lettuce, and flixweed. Seeding was done in the summer of 2019; however, weed control was not made in a timely manner so kochia overwhelmed the entire site. This example illustrates the importance of providing weed control early in the season to prevent weeds from outcompeting seeded grasses. Seeded grasses did establish later in the summer once kochia was successfully controlled and irrigation was provided. To help DEN project managers and contractors prevent similar situations from occurring, Appendix J provides simple guidelines for controlling annual weeds in a seeded site.

Adaptive Weed Management Program for Seeding Projects

1. Apply non-soil residual products for initial weed control – spring prior to seeding

i.e. glyphosate, 2,4-D, Vista for broad spectrum control

2. Drill-seed grasses in late-fall/early-winter

3. Monitor site in the following spring to determine weed invasion levels and grass establishment

i.e. annual weeds are common invaders for recently disturbed sites

4. Apply an herbicide mix to control broadleaf and grass weeds present

i.e. continue to use non-residual herbicides to prevent injuring young grasses

5. Continue to monitor site for the second and third growing season to assess grass establishment and size

i.e. grasses with multiple tillers and several leaves are considered well-established

6. Once grasses have become well-established, long soil residual herbicides can be applied to provide control for broad spectrum of species for multiple years without injuring grasses

i.e. Esplanade (7 oz/ac) and Method (8 oz/ac) applied in August or September; include Telar if white top and/or mustard species are present

REFERENCES

2014. *Mr. Clark's Place of Learning!* Available at: http://clarkiescourses.weebly.com/pasture-management.html. Accessed August 25, 2020.

Arizona Department of Transporation (ADOT). 2018. ADOT Roadside Vegetation Management Guidelines

Brannan, R. 2019. 2018 DEN Mowing Costs and Labor Hours.

CDA: Conservation Services District. Rules Pertaining to the Administration and Enforcement of the Colorado Noxious Weed Act. *In:* C. S. District (ed.

Chambers, J. C., B. A. Bradley, C. S. Brown, C. D'Antonio, M. J. Germino, J. B. Grace, S. P. Hardegree, R. F. Miller, and D. A. Pyke. 2014. Resilience to stress and disturbance, and resistance to *Bromus tectorum* L. invasion in cold desert shrublands of western North America. *Ecosystems* 17:360-375.

Clark, S. L. 2020. Using Herbicides to Restore Native Species and Improve Habitat on Rangelands and Wildlands. *Outlooks on Pest Management* 31:57-60.

Cleary, E. C., and R. A. Dolbeer. 2005. Wildlife Hazard Management at Airports: A Manual for Airport Personnel. Federal Aviation Administration

Colorado Department of Agriculture. 2004. Industrial and Right-of-Way Weed Control: Colorado Commercial Pesticide Application and Safety Training Study Guide. *In:* C. D. o. Agriculture (ed.: Colorado State University

Colorado Department of Agriculture. 2019. *Qualified Supervisor, Certified Operator, Private Applicator Licensing Information* Accessed February 11, 2020.

Colorado Department of Transportation. 2019. Standard Specifications for Road and Bridge Construction. *In:* CDOT (ed.

Colorado Environmental Pesticide Education Program. 2020. *Colorado Basic Pesticide Training* Available at: https://cepep.agsci.colostate.edu/.

Cox, R. D., and V. J. Anderson. 2004. Increasing native diversity of cheatgrass-dominated rangeland through assisted succession. *Rangeland Ecology and Management* 57:203-210.

Crider, F. J. 1955. Root-growth stoppage resulting from defoliation of grass. US Department of Agriculture.

Darmody, R., W. Daniels, J. Marlin, and D. Cremeens. 2009. Topsoil: What is it and who cares. National Meeting of the American Society of Mining and Reclamation, Billings, MT. Revitalizing the environment: Proven solutions and innovative approaches. ASMR, Lexington, KY. p. 237-269.

Darris, D. C. 2003. NRCS: Considerations for Establishing Native Grasses from Seed for Restoration, Revegetation, and Erosion Control in Western Washington and Western Oregon. Oregon.

Davies, K. W., and R. L. Sheley. 2011. Promoting Native Vegetation and Diversity in Exotic Annual Grass Infestations. *Restoration Ecology* 19:159-165.

Department, C. o. F. C. N. A. 2016. Restoration Plan 2016-2025. Colorado.

DiTomaso, J. M. 2000. Invasive weeds in rangelands: species, impacts, and management. *Weed science* 48:255-265.

Dudley, M. M., W. R. Jacobi, and C. S. Brown. 2014. Roadway deicer effects on the germination of native grasses and forbs. *Water, Air, & Soil Pollution* 225:1984.

EPA. 2013. *Water: Rivers & Streams*. Available at: https://archive.epa.gov/water/archive/web/html/streams.html. Accessed April 3, 2020.

Garvey, S. 2017. *John Deere looks to 2018*. Available at: https://www.country-guide.ca/columns/machinery-guide/john-deere-looks-to-2018/. Accessed June 19, 2020.

Herron, G. J., R. L. Sheley, B. D. Maxwell, and J. S. Jacobsen. 2001. Influence of nutrient availability on the interaction between spotted knapweed and bluebunch wheatgrass. *Restoration Ecology* 9:326-331.

Hobbs, R. J., and S. E. Humphries. 1995. An integrated approach to the ecology and management of plant invasions. *Conservation biology* 9:761-770.

Howery, L. D. 2016. Rangeland Management Before, During and After Drought. College of Agriculture, University of Arizona (Tucson, AZ).

Johnson, A. M. 2008. Best Practices Handbook for Roadside Vegetation Management Minnesota Department of Transportation: Wayzata, MN.

Kohlhepp, P. F., T. G. Sanders, C. C. Tackett, and R. W. Walters. 1995. Roadside Vegetation Managment: Final Guidelines Document for the Colorado Department of Transportation's Maintenance Manual.

Lockman, R., and D. Mount. 2009. To Mow or not Mow: Mowing prairie grasslands-the good and the bad.). Barnyards & Backyards. p. 5-6.

National Integrated Drought Information System. 2020. *Drought in Colorado* Available at: https://www.drought.gov/drought/states/colorado. Accessed August 8, 2020.

Nelson, J. R., A. Wilson, and C. J. Goebel. 1970. Factors influencing broadcast seeding in bunchgrass range. *Rangeland Ecology & Management/Journal of Range Management Archives* 23:163-170.

Nissen, S. 2018. Site Specific Weed Management and Restoration Strategies for Denver International Airport (DEN) Properties Denver International Airport.

Nissen, S. J. 2019. Improving Roadside Restoration Through Site Specific Training and Intra-Agency Cooperation. CDOT-2019-XX. Colorado State University.

Ozkan, H. E. 2016. *Boom Sprayer Calibration* Accessed May 1, 2020.

Pyke, D. A., T. A. Wirth, and J. L. Beyers. 2013. Does seeding after wildfires in rangelands reduce erosion or invasive species? *Restoration Ecology* 21:415-421.

Robins, J. G., K. B. Jensen, T. A. Jones, B. L. Waldron, M. D. Peel, C. W. Rigby, K. P. Vogel, R. B. Mitchell, A. J. Palazzo, and T. J. Cary. 2013. Stand establishment and persistence of perennial cool-season grasses in the Intermountain West and the Central and Northern Great Plains. *Rangeland ecology & management* 66:181-190.

Schilling, D. R. 2013. Denver Airport 2nd Largest in the World, Twice the Size of Manhattan.

Sebastian, D. 2020. Derigo and Plainview Programs in the West: 2020 Data and Recommendations Bayer Vegetation Management

Sebastian, D. J., S. L. Clark, S. J. Nissen, and D. K. Lauer. 2020. Total vegetation control: a comprehensive summary of herbicides, application timings, and resistance management options. *Weed Technology* 34:155-163.

Sebastian, D. J., M. B. Fleming, E. L. Patterson, J. R. Sebastian, and S. J. Nissen. 2017. Indaziflam: a new cellulose-biosynthesis-inhibiting herbicide provides long-term control of invasive winter annual grasses. *Pest Management Science* 73:2149-2162.

Sebastian, J. 2018. Ruth Roberts Open Space: Large Scale Weed Management and Revegetation). 2018 Weed Science Field Tour

Seshadri, A., and S. Sauer. 2020. Bringing back flowering plants and pollinators through effective control of invasive winter annual grasses with Esplanade® herbicide. Boulder County Open Space Small Grant Report.

Skaradek, W., and C. Miller. 2010. Plant fact sheet for saltgrass (*Distichlis spicata* (L.) *Greene*). *In:* C. M. P. M. C. USDA-Natural Resources Conservation Service (ed.

Stantec. 2019. Natural Resource Strategy: Existing Conditions Assessment.

Taliga, C. 2011. Technical Notes: Plant Suitability and Seeding Rates for Conservation Plantings in Colorado. U.S. Department of Agriculture.

TeeJet Technologies. 2013. A User's Guide to Spray Nozzles.

Truax Company Inc. *On the Go (OTG) Seed Drill*. Available at: https://www.truaxcomp.com/otg-seed-drill/. Accessed July 23, 2020.

Vogel, K. P., and R. A. Masters. 2001. Frequency grid--a simple tool for measuring grassland establishment. *Rangeland Ecology & Management/Journal of Range Management Archives* 54:653-655.

Western Regional Climate Center. 2020. *Period of Record Monthly Climate Summary*. Available at: https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?co2220. Accessed July 12, 2020.

Wilson, R. G., S. B. Orloff, D. L. Lancaster, D. W. Kirby, and H. L. Carlson. 2010. Integrating herbicide use and perennial grass revegetation to suppress weeds in noncrop areas. *Invasive Plant Science and Management* 3:81-92.

Young-Matthews, A., and S. R. Winslow. 2010. Plant fact sheet for manystem wildrye (*Leymus multicaulis*). *In:* P. M. C. USDA-Natural Resources Conservation Service (ed. Lockeford, CA.

CHAPTER 2: DOWNY BROME (*BROMUS TECTORUM* L.) AND NATIVE PLANT RESPONSES TO PRESCRIBED BURNING AND INDAZIFLAM

INTRODUCTION

Invasive winter annual grasses are negatively impacting rangeland in the western United States, with downy brome (*Bromus tectorum* L.) impacting the most acreage (DiTomaso 2000). Downy brome has invaded over 22 million hectares of rangeland and wildlands, and it has been projected that an additional 25 million hectares are susceptible to invasion (Duncan et al. 2004; Pellant and Hall 1994). Downy brome can germinate in diverse conditions, but typically germinates in early fall, and overwinters in a semi-dormant state. As one of the first plants to break dormancy in early spring, downy brome is able to take advantage of soil moisture and nutrients before native perennial vegetation come out dormancy (Beck 2009; D'Antonio and Vitousek 1992b). This competitive advantage and opportunistic life cycle has resulted in rapid expansion into perennial dominated rangelands, leading to devastating impacts on ecosystem functions (Duncan et al. 2004; Mack and Pyke 1983). Negative effects include altered nutrient cycling, decreased native vegetation, and increased fire frequency and severity (D'Antonio and Vitousek 1992b; Knapp 1996).

Increased wildfire frequency is often cited as a reason downy brome is so successful in outcompeting native plant communities (Melgoza et al. 1990; Young and Allen 1997). After producing seed and completing its annual life cycle in early summer, senescing plants will contribute to dense mats of litter, which slowly decompose (Evans and Young 1970; Klemmedson and Smith 1964). The accumulated litter increases wildfire frequency by providing a fine fuel layer, in addition to suppressing native vegetation germination and growth (D'Antonio and Vitousek 1992a; Ogle et al. 2003). This continuous, fine fuel source decreases the length of time between wildfires and increases their severity compared to historic fire regimes, resulting in detrimental impacts on native plant communities (Brooks 2002). Downy brome is also well-adapted to fire and quickly reinvades to dominate desirable plant communities (Melgoza et al. 1990; Wright and Klemmedson 1965; Young et al. 1976).

Alternatively, fires have been widely used as a tool by land managers to control winter annual grasses and stimulate the native plant community. Prescribed burning has been successful at providing short-term downy brome control and temporarily reducing the soil seed bank (DiTomaso et al. 2006; Keeley and McGinnis 2007). In addition, burning can lead to positive responses from the native plant community by removing accumulated litter; however, if there is limited fine fuel, fire intensity may not be enough to provide significant downy brome control and it will recover quickly after a fire (DiTomaso et al. 2006; DiTomaso et al. 1999; Keeley and McGinnis 2007; Kessler et al. 2015; Whisenant and Uresk 1990). Furthermore, this short window of control does not provide adequate time for the remnant plant community to recover (DiTomaso et al. 2006; Kessler et al. 2015). Thus, prescribed burning is not recommended for downy brome control unless it is integrated with other management strategies, such as herbicides (DiTomaso et al. 2006; Keeley and McGinnis 2007).

Herbicides are considered the most effective sequential management strategy for invasive winter annual grass control after burning. Imazapic and rimsulfuron are commonly used rangeland herbicides that provide pre- and post-emergent downy brome control, but the length of control is variable (< 2 years) due to short-term soil residual (Davison and Smith 2007; Elseroad and Rudd 2011; Kessler et al. 2015; Mangold et al. 2013; Sebastian et al. 2017a; Sebastian et al.

2017b; Sebastian et al. 2016; Wallace and Prather 2016). Indaziflam, a pre-emergent, soil residual herbicide that inhibits seedling establishment, provides downy brome control for 2 or more years (Clark et al. 2020; Sebastian et al. 2017a; Sebastian et al. 2016). Indaziflam's extended residual control creates the opportunity to start depleting the soil seed bank, extending the window for remnant plant communities to recover (Chambers et al. 2014; Sebastian et al. 2017a; Sebastian et al. 2017b; Sebastian et al. 2016).

When creating a management plan, remnant native plant communities must be considered in addition to downy brome control. Establishing healthy plant communities after removing downy brome aids in the restoration process and has the potential to prevent downy brome reinvasion (Elseroad and Rudd 2011). Treatments must be tailored to promote native vegetation rather than negatively impact them (Davies and Sheley 2011). At lower rates, imazapic can be selective on non-target vegetation; however, studies have shown it can injure perennial grasses (Kyser et al. 2007; Shinn and Thill 2004). Wallace and Prather (2016) also found that rimsulfuron can have low levels of injury on cool-season perennial grasses. Indaziflam does not negatively impact perennial grasses or forbs, and can lead to significant increases in native species biomass due to reductions in downy brome competition (Clark et al. 2019b; Clark et al. 2020; Koby et al. 2019; Sebastian et al. 2017a). An effective management plan that promotes native plant community recovery and provides multi-year downy brome control is essential to depleting the seed bank because seed viability is short (Sebastian et al. 2017b). Indaziflam takes advantage of this weakness to manage the soil seed bank with long-term residual control.

Integrating prescribed burning with herbicides, such as imazapic, has resulted in extended downy brome control and the release of remnant plant communities (Davies and Sheley 2011; Kessler et al. 2015; Kyser et al. 2007). It has been speculated that herbicide efficacy is often increased once surface litter is removed by burning (DiTomaso et al. 2006). Quantitative studies have found that 74% to 84% of imazapic, rimsulfuron, and indaziflam, are intercepted by high amounts of downy brome litter (Clark et al. 2019a; Kessler et al. 2015). Furthermore, Clark et al. (2019a) found that < 50% of indaziflam is recovered from litter with adequate rainfall (12- and 24-mm) while imazapic and rimsulfuron are almost completely released, suggesting irreversible binding to the litter is occurring with indaziflam (Carbonari et al. 2016). An herbicide's chemical properties influence binding to litter. A more lipophilic herbicide, such as indaziflam, is more prone to binding to lignin in litter compared to the hydrophilic herbicides, imazapic and rimsulfuron (Dao 1991; Shaner 2014). Although a large amount of herbicide is intercepted and bound to the litter, several studies indicate that indaziflam still provides consistent control in high-litter sites; however, at lower field use rates (44 g · ai · ha^{-1}) control is less consistent (Sebastian et al. 2017a). Therefore, integrating indaziflam treatments after prescribed burning could be beneficial for increasing herbicide efficacy, especially for lower indaziflam rates.

Indaziflam provides pre-emergent control only and relies on precipitation to be activated; therefore, it does not provide control of established plants. Past research has recommended combining indaziflam with a post-emergent herbicide, such as glyphosate, if applied after downy brome germination (Sebastian et al. 2017a). This combination provides immediate control of established plants; however, glyphosate does not have soil-residual activity and will not control plants that germinate after application (Beck 2009). This can lead to inconsistent control in the first year if indaziflam is not released from litter and activated by precipitation before new plants germinate (Clark et al. 2019a). Herbicides, such as imazapic and rimsulfuron, that have some soil-residual activity, need to be considered to provide not only post-emergent control, but also to provide short-term residual control. Sebastian et al. (2016) found that indaziflam plus rimsulfuron applied as a late-POST treatment provided significant downy brome control for 3 years. Although no published research has evaluated the combination of indaziflam plus imazapic for downy brome control, this combination should provide similar long-term results due to imazapic's ability to provide short-term residual control (Kessler et al. 2015; Kyser et al. 2013; Mangold et al. 2013). Combining indaziflam with either of these post-emergent herbicides can provide downy brome control after germination. This can extend the window in which post-emergent treatments can be applied with less injury to native species compared to glyphosate applications while increasing indaziflam's efficacy on sites with significant downy brome litter.

Following burning with herbicides can increase downy brome control duration; however, the sequential management of prescribed fire followed by indaziflam applications needs to be evaluated in terms of downy brome control and the response from remnant plant communities. While no published research has determined if removing litter using fire increases indaziflam efficacy, long-term downy brome control could be achieved using these integrated management strategies. We evaluated the effectiveness of combining burning with indaziflam alone and in combination with post-emergent herbicides for downy brome control and monitored the response of the remnant plant community in foothill shrublands.

MATERIALS AND METHODS

Site Description

The study was established in Boulder County, CO in 2018. Site 1 was located at the Rabbit Mountain Open Space (lat 40°14'32"N, long 105.12'36"0141°W) east of Lyons, CO. Site 2 was located at the Hall Ranch Open Space (lat 40°13'08" N, long 105°20'00"W) located southwest of Lyons, CO. Elevation at each site was 1773 m and 2041 m, respectively. Sites were approximately 18 km apart in the Foothills Shrubland region of the Great Plains ecoregion. The soil at site 1 was Baller stony sandy loam (loamy-skeletal, mixed, superactive, mesic Lithic Haplustolls), with 3.8% organic matter in the top 20 cm. The soil at site 2 was Cypher-Ratake families complex (gravelly sandy loam to gravelly coarse sandy loam, Paralithic Hapflustalfs), with 4.1% organic matter in the top 20 cm ([USDA-NRCS] U.S. Department of Agriculture and Natural Resources Conservations Service 2019). Site 1 was categorized as ~70% downy brome cover in the burned plots and ~60% cover in the non-burned plots. Site 2 had ~60% downy brome cover in the burned plots and ~40% to 50% cover in the non-burned plots. Each site also consisted of co-occurring perennial grass and forb communities, along with nonnative forbs (Table 8).

Annual precipitation data were collected from a weather station in Lyons, CO, located approximately 9 km from each site. Total annual precipitation for 2018 was 412 mm and 465 mm in 2019. In 2020, a statewide drought occurred in the first nine months of the year, only receiving 287 mm of precipitation, while the 11-year average between 2009 and 2020 for this same time period was 385 mm (Community Collaborative Rain 2020).

Experimental Design and Measurements

In September 2017, a prescribed burn was conducted at both sites to thin shrubs and promote native vegetation growth when downy brome was the early-seedling stage At each site, plots were established in the burned area as well as a non-burned area. The burned and non-burned plots were separated by a service road, in which the sites were conveniently located directly across from each other. In the burned and non-burned plots at each site, herbicide treatments were applied as a late post-emergent application in March 2018 to target downy brome at the two- to three-tiller stage. Herbicide treatments were applied to 3 by 9 m plots arranged in a split-block design with four replications, with burning as the main plot factor and herbicide treatments as the sub-plot factor. All herbicide treatments and rates are provided in Table 9. Treatments were applied using a CO_2 – pressurized backpack sprayer using 11002LP flat-fan nozzles (TeeJet Tech, Wheaton, IL). The backpack sprayer was pressurized to 206 kPa and calibrated to deliver 187 $L \cdot ha^{-1}$. All treatments included 0.25% v/v nonionic surfactant. Downy brome and desirable plant community responses to burning and herbicide treatments were evaluated in July 2019 and 2020. To evaluate downy brome, perennial grass, and perennial forb species responses to treatment effects, visual percent canopy cover was estimated using a line transect beginning in the middle of the 3 m side of the plot and oriented along the 9-m length of the plot. Cover estimation samples were taken at set intervals of 3 m and 6 m using a 0.75 m^2 gridded quadrat divided into 25, 15 cm by 15 cm squares to capture within plot variation. Each quadrat was positioned opposite of each other, right and left of the transect, at the set intervals to account for plant variability within each plot (Nyamai et al. 2011). The native plant community diversity was expressed as: (i) species richness, (ii) Shannon's diversity index *H*, and (iii) Simpson's diversity index *D*. Species richness was the average number of species counted in each of the 0.75 m^2 quadrats. Both diversity indices were calculated using the average percent cover data for the native plant community from the 0.75 m^2 quadrat observations.

$$H = -\sum p_i \ln p_i \qquad (1)$$

Shannon's diversity index (equation 1) was calculated where p_i is the proportion of the number of individuals in the ith species divided by the total number of species (n_i/N) (Krebs 1989).

$$D = 1 - \sum n(n\text{-}1) / \mathrm{N}(\mathrm{N}\text{-}1) \qquad (2)$$

Simpson's diversity index (equation 2) was calculated where *n* is the number of individuals for one species and N is the total number of species.

Statistical Analysis

A linear mixed-effects model was created to test the effects of treatment, burn type, and year on downy brome, perennial grass, and perennial forb cover, Shannon's diversity index, and Simpson's diversity index. Nonnative species were excluded from the cover and diversity analyses. Testing was done in the LME4 package in R v. 3.5.3, testing for effects at $\alpha = 0.05$ (R Core Team 2019). The fixed factors included in the model were treatment, year, burn type (burned or non-burned), and interactions for treatment and burn type, while block was treated as a random factor. Sites were analyzed separately for all variables due to variability in perennial grass and forb cover and differences in site characteristics. To meet the assumptions of normality, downy brome cover data were arcsine square root transformed. Main effects and interactions were considered significant at $\alpha < 0.05$. Significant main effects or interactions were further analyzed using the EMMEANS package in R to obtain all pairwise comparisons with a Tukey-Kramer adjustment (R Core Team 2019). Downy brome means and standard errors (SE) presented in tables are the original, non-transformed data. Species richness was analyzed using a generalized linear mixed model with a Poisson distribution after failing to reject the hypothesis that count data for species richness was from a Poisson distribution ($p = 1$ for both sites). The same factors used in the linear mixed model were used for the species richness analysis in the LME4 package (R Core Team 2019).

RESULTS

Herbicide Treatments

A linear mixed-effects model was used to test for significant differences among treatments at both sites ($\alpha < 0.05$). There were no significant differences found between treatments where indaziflam was combined with rimsulfuron or imazapic for any variables; therefore, values for these treatments were combined and will be referred to as indaziflam 44 or 73 g · ai · ha^{-1} + POST. Indaziflam 44 or 73 g · ai · ha^{-1} + glyphosate treatments were significantly different from indaziflam + POST treatments and were not combined.

Downy brome Response

Site 1

Burning before herbicide applications had a significant effect on treatment performance ($p = 0.0013$); therefore, treatments were compared between burned and non-burned plots within each year. Comparing control plots, it was possible to determine that burning alone resulted in lower downy brome cover 1 and 2 years after treatment (YAT) (Table 10). The mean cover for all herbicide treatments in the burned plots had significantly lower downy brome cover compared to the non-burned plots, 6.5% ± 1.2 (mean ± SE) compared to 19.8% ± 2.6, respectively ($p < 0.0001$).

In the non-burned plots, all indaziflam treatments significantly reduced downy brome cover compared to the non-burned control 1 and 2 YAT; however, downy brome cover with the current industry standard of imazapic + glyphosate was similar to the control 1 and 2 YAT (Table 10). In the burned plots, all treatments except for indaziflam 73 g · ai · ha^{-1} + glyphosate had less cover than the burned control 1 and 2 YAT. For both year, cover was lower in burned treatments with indaziflam + POST (44 and 73 g · ai · ha^{-1}), indaziflam alone (44 and 73 g · ai ·

ha^{-1}), and imazapic + glyphosate (Table 10). Indaziflam applied alone at the highest rate significantly reduced downy brome cover 1 and 2 YAT, with or without litter removal through burning.

Downy brome Response

Site 2

At site 2, burning also had a significant impact on herbicide performance ($p = 0.0054$), so treatments were compared across the burned and non-burned plots for each year. We saw similar impacts of burning alone on downy brome cover with lower cover in the burned control compared to the non-burned control 1 YAT. By the second year, downy brome cover was higher in the burned control, indicating that burning alone only reduced downy brome cover in the short-term (Table 10). All herbicide treatments performed better when applied after burning. The average downy brome cover across all burned herbicide treatments was 7% ± 1.5 compared to 15.5% ± 1.7 in the non-burned plots 2 YAT. Our data supports previous findings that prescribed burning combined with soil-applied herbicides can increase the longevity of downy brome control (Kessler et al. 2015).

Desirable Plant Community Cover Responses

Site 1

The interaction between burning and herbicide treatments was not significant at site 1 ($p = 0.762$); however, the burning effect did positively influence grass community cover ($p = 0.033$). The community was predominately western wheatgrass *(Pascopyrum smithii)*, Canada bluegrass (*Poa compressa)*, and Kentucky bluegrass (*Poa pratensis)*. The cool-season grass dominated community increased in the burned plots compared to the non-burned plots, both 1 and 2 YAT (15% and 20% increase, respectively; Table 11). Herbicide treatment also impacted grass cover ($p = 0.0157$). Indaziflam 73 g · ai · ha^{-1} + POST increased grass cover to 33% ± 5.8

across the burned and non-burned plots, whereas the control plots had 15% ± 6.3 cover ($p = 0.0071$).

Perennial forb cover was not influenced by herbicide treatments ($p = 0.277$); therefore, treatments were analyzed by burn type or year which were both significant at $p < 0.0001$. Total forb cover was lower 2 YAT compared to 1 YAT (Table 11). Unlike perennial grass cover in the burned plots, forb cover was reduced in the burned plots both years compared to the non-burned plots.

Native shrubs and sub-shrubs were combined as one functional group to evaluate burning and treatment effects. Cover was not influenced by burning, herbicide treatment, or year (Table 11). The burn type by treatment interaction did impact shrub/sub-shrub cover ($p < 0.046$). In the non-burned plots, indaziflam 44 $g \cdot ai \cdot ha^{-1}$ had 7.62% ± 2.03 shrub/sub-shrub cover, whereas indaziflam 102 $g \cdot ai \cdot ha^{-1}$ had 25.81% ± 6.35 cover.

Site 2

At site 2, the interaction between burning and herbicide treatments had no significant effects to grass cover ($p = 0.107$). Similar to site 1, grass cover was reduced in the second year ($p < 0.012$; Table 11). There was a treatment effect ($p = 0.048$), but after a post hoc Tukey test, it revealed no significant differences between individual treatment means.

Perennial forb cover was not influenced by the burn type by treatment interaction ($p =0.381$). Herbicide treatments did influence perennial forb cover ($p = 0.0146$); however, the only difference in cover was observed between indaziflam 44 $g \cdot ai \cdot ha^{-1}$ + glyphosate and the control when averaged across burn type and year (29.8% ± 5.6 vs. 17.7% ± 3.3, $p = 0.0468$). Burn type and year also impacted forb cover ($p = 0.0017$ and $p < 0.0001$, respectively). Perennial forb cover was reduced in the second year (Table 11). Unlike the forb cover at site 1, cover increased in the burned plots compared to the non-burned plots. This increase in forb community is likely due to the plant composition at this site being more forb dominated in the burned plots compared to the non-burned plots.

Shrub/sub-shrub cover was impacted by the burn type and year effects (p = 0.0014 and p <0.003, respectively). Compared to the non-burned plots, burning increased cover 1 and 2 YAT. Regardless of burning, cover was lower 2 YAT compared to 1 YAT (Table 11). Similar to the other two functional plant groups at site 1 and 2, cover likely decreased due to lower precipitation, rather than herbicide treatment or burning impacts. There was no significant interaction between burning and treatments (p = 0.863).

Species Richness and Diversity Response

Functional plant group cover data were used to estimate the quantity of each group in a plot; however, species richness and diversity indices were used to further evaluate the effect of burning and herbicide treatments on species diversity. The list of co-occurring species present at both sites can be found in Table 8.

Site 1

Species richness was not significantly impacted by the interaction between burning and treatment, or the year, burn type, or treatment effects (p = 0.597, p = 0.096, p = 0.318, and p = 0.856, respectively). The mean number of individual species in the non-burned plots was 5.55 ± 0.18 and in the burned plots 5.42 ± 0.19 1 YAT and stayed consistent 2 YAT for both burn types (Table 12). Shannon's diversity and Simpson's diversity had similar responses to all effects (Table 12). Diversity was not impacted by year, burning, or treatments (Shannon's diversity: p = 0.771, p = 0.376, and p = 0.269, respectively; Simpson's index of diversity: p = 0.623, p = 0.754, p = 0.829, respectively). Both diversity indices are dependent on species richness, indicating that the lack of changes in diversity measures were driven by the lack of change in species richness.

Site 2

Overall native plant community richness and diversity were greater in the burned plots compared to the non-burned plots. Burn type was the only significant effect on species richness ($p < 0.001$); therefore, burn type was further analyzed across treatment and year. Species richness was significantly greater in the burned plots for both year (Table 12), with a mean richness of 6.6 ± 0.21 in the non-burned plots compared to 9.9 ± 0.3 in the burned plots. Shannon's diversity was significantly increased by burning and year ($p < 0.0001$ and $p < 0.0002$, respectively). Simpson's diversity significantly increased in the burned plots compared to the non-burned plots 1 and 2 YAT. ($p < 0.0001$; Table 12). Although site comparisons were not analyzed to determine differences between sites, species richness and diversity measurements were greater overall at site 2 compared to site 1.

DISCUSSION

Downy Brome Response

Our study supports the results from similar research evaluating downy brome control using prescribed burning followed by herbicide applications (Calo et al. 2012; Davies and Sheley 2011; Kessler et al. 2015; Kyser et al. 2007). As noted in Sheley et al. (2007), due to the difficulty of replicating prescribed burns, we could not perform standard statistical analyses; however, the multiple sites in this study and in other studies have demonstrated that burning does increase control efficacy for soil-applied herbicides (Calo et al. 2012, Davies and Sheley 2011, Kessler et al. 2015, Sheley et al. 2017). Burning before applying indaziflam alone or combined with POST herbicides significantly increased downy brome control. After 2 years, control with indaziflam at the lowest rate, alone or with glyphosate, decreased at both sites in the non-burned plots, but with the addition of burning, treatments were still effective at this lower rate (Table 10). After 2+ years, the lowest field use rate of indaziflam starts to lose efficacy when compared to higher use rates, especially in sites with high litter (Clark et al. 2020; Sebastian et al. 2017a). This is likely due to indaziflam's tendency to easily adsorb to winter annual grass litter, preventing the full rate from reaching the soil to be activated (Clark et al. 2019a).

Indaziflam at the two lower rates combined with glyphosate were inconsistent between sites in the burned and non-burned plots. Inconsistent downy brome control has been reported when indaziflam was combined with glyphosate (Quicke Personal communication). A common recommendation is to combine glyphosate with indaziflam when making winter dormancy applications; however, our results suggest that there can be inconsistencies in control when this combination is applied in early spring (Table 10). Therefore, it is important to evaluate other effective post-emergent herbicides that could be combined with indaziflam to increase application flexibility. In our study, we found that treatments in the non-burned plots with POST herbicides, rimsulfuron and imazapic, outperformed the combination with glyphosate. The combination of burning with lower indaziflam + POST rates performed significantly better, reducing downy brome cover to < 1%, 2 YAT. These two soil active herbicides provided effective foliar and short-term residual control when applied as a post-emergent treatment (Mangold et al. 2013; Wallace and Prather 2016). When combined with indaziflam, rimsulfuron and imazapic increased downy brome control as they provided immediate control, while also providing residual control for plants that germinated before indaziflam was incorporated into the soil. Glyphosate does not provide that short-term residual control that is needed to cover this time period between indaziflam application and activation. This information is critical for land managers applying indaziflam when the desirable plant community is not dormant. Using these selective, residual herbicides with indaziflam provides more flexibility so that herbicide applications can be made with less injury to desirable vegetation while achieving initial downy brome control.

Herbicides are intercepted by litter, reducing the amount of herbicide reaching the soil (Clark et al. 2019a; DiTomaso et al. 2006; Kessler et al. 2015; Monaco et al. 2005). Indaziflam is a lipophilic herbicide and adsorbs more to litter compared to water-soluble herbicides, rimsulfuron or imazapic (Clark et al. 2019a). In our study, we found that treatments with higher indaziflam rates provided adequate downy brome control in the non-burned plots; however, there were some inconsistencies (Table 10), suggesting that some indaziflam was bound to litter, resulting in reduced efficacy. On the other hand, in the burned plots, herbicide efficacy significantly increased, which is likely due to litter being removed by burning, allowing for more herbicide to reach the soil. These data suggest that litter removal can be very beneficial when using indaziflam, especially when using lower rates. Previous observations have shown that control with indaziflam at 44 g · ai · ha^{-1} usually declines by the second season after treatment in sites where litter is present (Sebastian et al. 2017a), but with the addition of burning, control was maintained for 2 YAT at this rate. Additionally, indaziflam 73 g · ai · ha^{-1} + POST and indaziflam 102 g · ai · ha^{-1} treatments reduced downy brome cover to 0% in the burned plots throughout the study duration. Although the non-burned plots had a > 90% reduction in cover with these treatments, removing the litter through burning before applying the treatments eliminated downy brome cover.

In sites that have not been burned, higher indaziflam rates combined with POST herbicides, imazapic or rimsulfuron, would be an effective option for land managers. Even though our study illustrates increased control in indaziflam treatments with litter removal, previous studies have suggested that soil-applied herbicides adsorbed to litter can be slowly released as the litter decays and be incorporated in the soil to extend control (Dao 1991). We did observe that treatments with indaziflam provided long-term, effective control in the non-burned plots, indicating that indaziflam at higher rates significantly reduced downy brome cover compared to the non-burned control and imazapic treatment (Table 10). It is important to combine higher indaziflam rates (i.e. 73 $g \cdot ai \cdot ha^{-1}$) with short-residual post-emergent herbicides to provide immediate downy brome control once germination has occurred. Providing immediate control would allow time for indaziflam to be removed from the litter by precipitation and become incorporated into the soil. Indaziflam continues to be an effective control option for sites where litter is present, but for situations in which burning is desirable to rejuvenate native plant communities infested with downy brome, indaziflam can be used as a sequential management strategy with burning to increase and prolong control.

Desirable Plant Community Cover Response

While we did observe increased grass cover due to burning at only one site, other studies have reported significant increases in grass community biomass and cover after burning (Davies and Sheley 2011; DiTomaso et al. 1999; Kessler et al. 2015). More importantly, perennial grass cover did not decrease with the use of indaziflam, alone or in combination with glyphosate, rimusulfuron, or imazapic, indicating no negative impacts to grass cover from the herbicide treatments. Additionally, once remnant grasses are released from winter annual grass competition and reduced plant litter, perennial grass cover and biomass can increase (Clark et al. 2019b; Koby et al. 2019; Sebastian et al. 2017a; Sebastian et al. 2017c; Sebastian et al. 2016).

The native forb community responded differently to burning compared to the grass community (Table 11). Changes in cover following downy brome control could be associated with differences in the pretreatment densities for these species' groups (Monaco et al. 2005), where the forb community was more dominant in the burned plots at site 2 compared to the non-burned plots. Although the forb community responded differently at each site, we can confirm that no herbicide treatments decreased native forb cover. Other studies have reported that perennial forbs responded favorably when burning was combined with imazapic to control downy brome (Kessler et al. 2015; Kyser et al. 2013; Monaco et al. 2005). The current study is the first to report no negative impacts on the perennial forb community with the combination of burning followed by indaziflam. For land managers, indaziflam can be an effective tool to control downy brome in areas with diverse remnant plant communities (Clark et al. 2019b; Sebastian et al. 2017a).

Species Richness and Diversity Response

The increase in species diversity at site 2 is likely due to the increase in species richness and forb cover observed in the burned plots. Although species diversity was different between sites, these responses suggest that burning combined with indaziflam has the potential to increase species diversity. The level of response will depend on the remnant plant community at the site, as we found in this study (Davies and Svejcar 2008; DiTomaso et al. 2006). Burning is an effective tool for increasing native plant diversity by making more resources available after removing downy brome litter and eliminating competition. The native plant community benefits from increased resource availability, but only in the short-term because downy brome will re-establish from the soil seed bank (DiTomaso et al. 2006; DiTomaso et al. 1999; Keeley and McGinnis 2007; Kessler et al. 2015; Knapp and Seastedt 1986). Burning combined with indaziflam can have long-term beneficial effects by maintaining and improving plant community diversity while providing multi-year downy brome control. Effective winter annual grass control in areas with remnant desirable vegetation can begin the passive restoration process (Davies and Svejcar 2008). In addition, for sites dominated by a cool-season, perennial grass community, this program could promote forb establishment by removing perennial and annual grass litter and extending downy brome control with indaziflam treatments (DiTomaso et al. 2006; DiTomaso et al. 1999).

MANAGEMENT IMPLICATIONS

Indaziflam has proven to be a very effective tool for restoring sites that have been degraded by invasive winter annual grasses. This long-term residual control provides the opportunity to target the soil seed bank, releasing the desirable plant community. In this study, burning extended downy brome control for several indaziflam treatments when compared to non-burned treatments, likely due to removing accumulated surface litter. Indaziflam at all rates plus POST herbicides and indaziflam alone at the highest labeled rate (102 g · ai · ha^{-1}) were more consistent in burned plots compared to non-burned plots, resulting in ≤ 1% downy brome cover for two seasons. Applying a post-emergent herbicide, such as imazapic or rimsulfuron, with higher indaziflam rates can be an option for land managers controlling downy brome in arid sites where litter is present. Imazapic and rimsulfuron will provide post-emergent control for established downy brome and residual control for plants that germinate before indaziflam is activated by precipitation. For sites where litter has been removed by prescribed burning, lower labelled rates of indaziflam can be an effective option as more of the herbicide will reach the soil to control germinating plants and provide multi-season control; however, 73 $g \cdot ai \cdot ha^{-1}$ is the highest use rate that can be applied in grazed sites. Using prescribed burning and indaziflam as an integrated management system did not negatively impact the native plant community; rather, this combination helped increase or maintain species diversity. Removing the litter layer and providing long-term downy brome control is beneficial for sites with remnant plant communities as competition is removed and ecosystem functions are improved. In addition, our study shows that indaziflam combined with a selective, post-emergent herbicide is a viable option for land managers controlling downy brome in sites with a desirable plant community, as it can extend the window in which applications can be made without non-target injury. Ultimately, prescribed burning combined with indaziflam is an effective management option to restore degraded open spaces, natural areas, and grazed rangeland.

Table 8. List of species occurring at site 1 and site 2 with their functional group and nativity status[1].

Scientific Name	Common Name	Site 1	Site 2	Functional Group	Nativity
Alyssum simplex	Rudolphi alyssum	X	X	Forb	Nonnative
Ambrosia psilostachya	Western ragweed	X	X	Forb	Native
Andropogon geradii	Big bluestem	X		Grass	Native
Antennaria Gaertn.	Pussytoes	X	X	Forb	Native
Artemisia dracunculus	Tarragon	X	X	Sub-shrub	Native
Artemisia frigida	Fringed sagebrush	X	X	Sub-shrub	Native
Artemisisa ludoviciana	White sagebrush	X	X	Sub-shrub	Native
Astragalus agrestris	Purple milkvetch	X	X	Forb	Native
Astragalus flexuosus	Flexile milkvetch	X	X	Forb	Native
Astragalus laxmanii	Laxmann's milkvetch		X	Forb	Native
Astragalus spp.	Unknown		X	Forb	Native
Boechera stricta	Canada rockcress	X	X	Forb	Native
Bouteloua dactyolides	Buffalograss	X	X	Grass	Native
Bouteloua gracilis	Blue grama	X		Grass	Native
Bromus tectorum	Downy brome	X	X	Grass	Nonnative
Comandra umbellata	Bastard toadflax		X	Forb	Native
Cryptantha virgata	Miner's candle		X	Forb	Native
Elymus elymoides	Bottlebrush squirreltail		X	Grass	Native
Ericameria nauseosa	Rubber rabbitbrush	X	X	Shrub	Native
Erigeron divergens	Spreading fleabane	X		Forb	Native
Erigeron flagellaris	Trailing fleabane	X	X	Forb	Native
Eriogonum umbellatum	Sulfur-flower buckwheat	X	X	Forb	Native
Eriogonum jamesii	James' buckwheat		X	Forb	Native
Erodium cicutarium	Redstem filaree	X		Forb	Nonnative
Erysimum capitatum	Western wallflower		X	Forb	Native
Euphorbia brachycera	Horned spurge		X	Forb	Native
Gaillardia aristata	Blanketflower	X	X	Forb	Native
Geranium caespitosum	Parry’s Geranium		X	Sub-shrub	Native
Grindelia squarrosa	Curlycup gumweed	X	X	Forb	Native
Helianthus pumilus	Little sunflower	X	X	Forb	Native
Hesperostipa comata	Needle-and-thread	X	X	Grass	Native
Heterotheca villosa	Hairy false goldenaster	X	X	Sub-shrub	Native
Hypericum perforatum	Common St. Johnswort	X	X	Forb	Nonnative
Gutierrezia sarothrae	Broom snakeweed		X	Shrub	Native
Koeleria macrantha	Prairie Junegrass	X	X	Grass	Native
Linarius dalmatica	Dalmatian toadflax	X	X	Forb	Nonnative
Liatris punctata	Dotted blazing star	X	X	Forb	Native
Lupinus argenteus	Silvery lupine	X		Forb	Native

Mirabilis hirsuta	Hairy four o'clock		X	Forb	Native
Opuntia polyacantha	Plains pricklypear	X	X	Shrub	Native
Pascopyrum smithii	Western wheatgrass	X	X	Grass	Native
Plantago patagonica	Woolly plantain	X		Forb	Native
Poa compressa	Canada bluegrass	X	X	Grass	Nonnative
Poa pratensis	Kentucky bluegrass	X	X	Grass	Nonnative
Potentilla hippiana	Woolly cinquefoil		X	Forb	Native
Psoralidium tenuiflorum	Slimflower scurfpea	X	X	Forb	Native
Ratibida columnifera	Upright prairie coneflower	X	X	Forb	Native
Rosa woodsii	Woods' rose		X	Forb	Native
Tragopogon dubius	Yellow salsify	X	X	Forb	Nonnative
Rhus trilobata	Skunkbush sumac	X		Shrub	Native
Senecio spartisoides	Broom-like ragwort		X	Sub-shrub	Nonnative
Silene drumondii	Drummond's campion		X	Forb	Native
Solidago altissima	Tall goldenrod	X		Forb	Native
Sphaeralcea coccinea	Scarlet globemallow	X		Forb	Native
Symphyotrichum falcatum	White prairie aster	X	X	Forb	Native
Thlaspi arvense	Field pennycress	X		Forb	Nonnative
Verbascum blattaria	Moth mullein	X	X	Forb	Nonnative
Yucca glauca	Soapweed	X	X	Shrub	Native

[1] Taxonomic information for species were collected from the USDA-NRCS Plants Database.

Table 9. Herbicide treatments and rates applied in evaluating downy brome control and desirable species responses.

Herbicide treatments[1]	**Rate ($g \cdot ha^{-1}$)**	**Manufacturer**
Indaziflam	44 ai	Bayer CropScience, Research Triangle Park, NC
Indaziflam	73 ai	Bayer CropScience, Research Triangle Park, NC
Indaziflam	102 ai	Bayer CropScience, Research Triangle Park, NC
Indaziflam + glyphosate	44 ai + 755 ae	Bayer CropScience, Research Triangle Park, NC
Indaziflam + glyphosate	73 ai + 755 ae	Bayer CropScience, Research Triangle Park, NC
Indaziflam + POST (imazapic or rimsulfuron)	44 ai + 63 ai or 123 ai	Bayer CropScience, Research Triangle Park, NC BASF Specialty Products, Research Triangle Park, NC
Indaziflam + POST (imazapic or rimsulfuron)	73 ai + 63 ai or 123 ai	Bayer CropScience, Research Triangle Park, NC BASF Specialty Products, Research Triangle Park, NC
Imazapic + glyphosate	123 ai + 73 ae	BASF Specialty Products, Research Triangle Park, NC Bayer CropScience, Research Triangle Park, NC

[1] NIS at 0.25% v/v was added to all herbicide treatments.

Table 10. Mean percentages for downy brome cover at site 1 and site 2 for 1 and 2 years after herbicide treatments (YAT) were applied. Data are displayed to interpret the burn type by herbicide treatment interaction. Treatments in the non-burned and burned plots are compared within each year and site ($P < 0.05$). Means followed by different letters indicate a significant difference at the $P < 0.05$ level.

		Site 1 - Rabbit Mountain		Site 2 - Hall Ranch	
		1 YAT	**2 YAT**	**1 YAT**	**2 YAT**
Burn type	**Treatment**	**Brome cover %**		**Brome cover %**	
Non-burned	Control	37 g	69 g	51 f	33 f
	Indaziflam 44	22 ef	24 ef	15 cd	13 cd
	Indaziflam 44 + Glyphosate	14 cdef	8 cdef	15 cde	18 cde
	Indaziflam 44 + POST	13 de	15 de	3 bc	9 bc
	Indaziflam 73	12 de	12 de	3 ab	4 ab
	Indaziflam 73 + Glyphosate	9 cde	9 cde	25 def	24 def
	Indaziflam 73 + POST	8 bcd	4 bcd	1 ab	4 ab
	Indaziflam 102	4 abcd	7 abcd	3 bc	12 bc
	Imazapic + Glyphosate	34 fg	31 fg	35 ef	23 ef
Burned	Control	14 ef	32 ef	21 ef	43 ef
	Indaziflam 44	6 bcd	7 bcd	0 ab	1 ab
	Indaziflam 44 + Glyphosate	3 abcd	1 abcd	2 abc	6 abc
	Indaziflam 44 + POST	1 ab	1 ab	0 a	0 a
	Indaziflam 73	1 abc	4 abc	0 ab	2 ab
	Indaziflam 73 + Glyphosate	11 cde	10 cde	0 ab	7 ab
	Indaziflam 73 + POST	0 a	0 a	0 a	0 a
	Indaziflam 102	0 a	0 a	0 a	0 a
	Imazapic + Glyphosate	5 abcd	4 abcd	3 abc	4 abc

Table 11. Desirable plant community cover at site 1 and site 2. Values are provided for 1 and 2 years after treatment (YAT). Means followed by the same lowercase letter do not differ significantly between burn type within each year in the same row ($P < 0.05$). Means followed by the same uppercase letter do not differ significantly between year and are averaged across burn type in the same row ($P < 0.05$).

		Site 1 - Rabbit Mountain			
		1 YAT		**2 YAT**	
% Cover		Non-burned	Burned	Non-burned	Burned
Perennial grass		28.2 a A	33.1 b A	19.2 a B	24.1 b B
Perennial forbs		36.1 a A	19 b A	15.4 a B	11.8 b B
Shrubs/sub-shrubs		17.4 a A	14.6 a A	17.1 a A	14.5 a A
		Site 2 - Hall Ranch			
		1 YAT		**2 YAT**	
		Non-burned	Burned	Non-burned	Burned
Perennial grass		40.6 a A	36.7 a A	34.7 a B	30.7 a B
Perennial forbs		18.1 a A	25.1 b A	12.8 a B	17.6 b B
Shrubs/sub-shrubs		20 a A	23.7 b A	12.5 a B	19.4 b B

Table 12. Desirable plant diversity responses at site 1 and site 2. Values are provided for 1 and 2 years after treatment (YAT). Means followed by the same lowercase letter do not differ significantly between burn type within each year in the same row ($P < 0.05$). Means followed by the same uppercase letter do not differ significantly between year and are averaged across burn type in the same row ($P < 0.05$).

		Site 1 - Rabbit Mountain			
		1 YAT		**2 YAT**	
Diversity Measurements		Non-burned	Burned	Non-burned	Burned
Richness		5.55 a A	5.42 a A	5.5 a A	5.45 a A
Shannon's		1.24 a A	1.22 a A	1.28 a A	1.27 a A
Simpson's		0.676 a A	0.629 a A	0.649 a A	0.648 a A
		Site 2 - Hall Ranch			
		1 YAT		**2 YAT**	
		Non-burned	Burned	Non-burned	Burned
Richness		6.31 a A	9.23 b A	6.95 a A	9.97 b A
Shannon's		1.41 a A	1.77 b A	1.56 a B	1.92 b B
Simpson's		0.742 a A	0.803 b A	0.671 a B	0.792 b B

REFERENCES

[USDA-NRCS] U.S. Department of Agriculture, and Natural Resources Conservations Service. 2019. *Web Soil Survey*. Available at: https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx. Accessed September 11, 2020.

Beck, K. G. 2009. *Downy brome (Bromus tectorum) and Japanese brome (Bromus japonicus) biology, ecology, and management*. Available at: https://www.nwcb.wa.gov/pdfs/Downy_brome_and_Japanese_brome_literature_review_Colorado_DRMS_Dec_09.pdf. Accessed February 11, 2020.

Brooks, M. L. 2002. Peak fire temperatures and effects on annual plants in the Mojave Desert. *Ecological Applications* 12:1088-1102.

Calo, A., S. Brause, and S. Jones. 2012. Integrated treatment with a prescribed burn and postemergent herbicide demonstrates initial success in managing cheatgrass in a northern Colorado natural area. *Natural Areas Journal* 32:300-305.

Carbonari, C. A., G. L. Gomes, M. L. Trindade, J. R. Silva, and E. D. Velini. 2016. Dynamics of sulfentrazone applied to sugarcane crop residues. *Weed science* 64:201-206.

Chambers, J. C., B. A. Bradley, C. S. Brown, C. D'Antonio, M. J. Germino, J. B. Grace, S. P. Hardegree, R. F. Miller, and D. A. Pyke. 2014. Resilience to stress and disturbance, and resistance to *Bromus tectorum* L. invasion in cold desert shrublands of western North America. *Ecosystems* 17:360-375.

Clark, S. L., P. V. da Silva, F. E. Dayan, S. J. Nissen, and D. J. Sebastian. 2019a. The Influence of Winter Annual Grass Litter on Herbicide Availability. *Weed Science* 67:702-709.

Clark, S. L., D. J. Sebastian, S. J. Nissen, and J. R. Sebastian. 2019b. Effect of indaziflam on native species in natural areas and rangeland. *Invasive Plant Science and Management* 12:60-67.

Clark, S. L., D. J. Sebastian, S. J. Nissen, and J. R. Sebastian. 2020. Evaluating winter annual grass control and native species establishment following applications of indaziflam on rangeland *Invasive Plant Science and Management*.

Community Collaborative Rain, S., and Hail Network. 2020. *Colorado Station Precipitation Summary.* Available at: https://www.cocorahs.org/ViewData/StationPrecipSummary.aspx. Accessed September 7, 2020

D'Antonio, C. M., and P. M. Vitousek. 1992a. Biological invasions by exotic grasses, the grass/fire cycle, and global change. *Annual review of ecology and systematics* 23:63-87.

D'Antonio, C. M., and P. M. Vitousek. 1992b. Biological invasions by exotic grasses, the grass/fire cycle, and global change. Annual review of ecology and systematics. p. 63-87.

Dao, T. H. 1991. Field decay of wheat straw and its effects on metribuzin and S-ethyl metribuzin sorption and elution from crop residues. *Journal of environmental quality* 20:203-208.

Davies, K. W., and R. L. Sheley. 2011. Promoting Native Vegetation and Diversity in Exotic Annual Grass Infestations. *Restoration Ecology* 19:159-165.

Davies, K. W., and T. J. Svejcar. 2008. Comparison of medusahead-invaded and noninvaded Wyoming big sagebrush steppe in southeastern Oregon. *Rangeland Ecology & Management* 61:623-629.

Davison, J. C., and E. G. Smith. 2007. Imazapic provides 2-year control of weedy annuals in a seeded Great Basin fuelbreak. *Native Plants Journal* 8:91-96.

DiTomaso, J. M. 2000. Invasive weeds in rangelands: species, impacts, and management. *Weed science* 48:255-265.

DiTomaso, J. M., M. L. Brooks, E. B. Allen, R. Minnich, P. M. Rice, and G. B. Kyser. 2006. Control of invasive weeds with prescribed burning. *Weed Technology* 20:535-548.

DiTomaso, J. M., G. B. Kyser, and M. S. Hastings. 1999. Prescribed Burning For Control of Yellow Starthistle (*Centaurea solstitialis*) and Enhanced Native Plant Diversity. *Weed Science* 47:233-242.

Duncan, C. A., J. J. Jachetta, M. L. Brown, V. F. Carrithers, J. K. Clark, J. M. DiTOMASO, R. G. Lym, K. C. McDANIEL, M. J. Renz, and P. M. Rice. 2004. Assessing the Economic, Environmental, and Societal Losses from Invasive Plants on Rangeland and Wildlands1. *Weed Technology* 18:1411-1416.

Elseroad, A. C., and N. T. Rudd. 2011. Can imazapic increase native species abundance in cheatgrass (Bromus tectorum) invaded native plant communities? *Rangeland Ecology & Management* 64:641-648.

Evans, R. A., and J. A. Young. 1970. Plant litter and establishment of alien annual weed species in rangeland communities. *Weed science*:697-703.

Keeley, J. E., and T. W. McGinnis. 2007. Impact of prescribed fire and other factors on cheatgrass persistence in a Sierra Nevada ponderosa pine forest. *International Journal of Wildland Fire* 16:96-106.

Kessler, K. C., S. J. Nissen, P. J. Meiman, and K. G. Beck. 2015. Litter Reduction by Prescribed Burning Can Extend Downy Brome Control. *Rangeland Ecology & Management* 68:367-374.

Klemmedson, J. O., and J. G. Smith. 1964. Cheatgrass (Bromus tectorum L.). *The Botanical Review* 30:226-262.

Knapp, A., and T. Seastedt. 1986. Detritus accumulation limits productivity of tallgrass prairie. *BioScience* 36:662-668.

Knapp, P. A. 1996. Cheatgrass (*Bromus tectorum* L) dominance in the Great Basin Desert: history, persistence, and influences to human activities. *Global environmental change* 6:37-52.

Koby, L. E., T. S. Prather, H. Quicke, J. Beuschlein, and I. C. Burke. 2019. Management of Ventenata dubia in the Inland Pacific Northwest with Indaziflam. *Invasive Plant Science and Management*:1-25.

Krebs, C. J. 1989. Ecological Methodology. Harper & Row New York.

Kyser, G. B., J. M. DiTomaso, M. P. Doran, S. B. Orloff, R. G. Wilson, D. L. Lancaster, D. F. Lile, and M. L. Porath. 2007. Control of medusahead (Taeniatherum caput-medusae) and other annual grasses with imazapic. *Weed Technology* 21:66-75.

Kyser, G. B., R. G. Wilson, J. Zhang, and J. M. DiTomaso. 2013. Herbicide-assisted restoration of Great Basin sagebrush steppe infested with medusahead and downy brome. *Rangeland Ecology & Management* 66:588-596.

Mack, R. N., and D. A. Pyke. 1983. The demography of Bromus tectorum: variation in time and space. *The Journal of Ecology*:69-93.

Mangold, J., H. Parkinson, C. Duncan, P. Rice, E. Davis, and F. Menalled. 2013. Downy brome (*Bromus tectorum*) control with imazapic on Montana grasslands. *Invasive Plant Science and Management* 6:554-558.

Melgoza, G., R. S. Nowak, and R. J. Tausch. 1990. Soil water exploitation after fire: competition between Bromus tectorum (cheatgrass) and two native species. *Oecologia* 83:7-13.

Monaco, T. A., T. M. Osmond, and S. A. Dewey. 2005. Medusahead control with fall-and spring-applied herbicides on northern Utah foothills. *Weed Technology* 19:653-658.

Nyamai, P. A., T. S. Prather, and J. M. Wallace. 2011. Evaluating Restoration Methods Across a Range of Plant Communities Dominated by Invasive Annual Grasses to Native Perennial Grasses. *Invasive Plant Science and Management* 4:306-316.

Ogle, S. M., W. A. Reiners, and K. G. Gerow. 2003. Impacts of exotic annual brome grasses (Bromus spp.) on ecosystem properties of northern mixed grass prairie. *The American midland naturalist* 149:46-58.

Pellant, M., and C. Hall. 1994. Distribution of two exotic grasses on intermountain rangelands: status in 1992. U.S. Department of Agriculture, Forest Service Intermountain Research Station General Technical Report INT-313: Boise, ID. Ogden, UT

p. 109-112 in Monsen SB, Kitchen SG, compilers.

R Core Team. 2019. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing

Sebastian, D. J., M. B. Fleming, E. L. Patterson, J. R. Sebastian, and S. J. Nissen. 2017a. Indaziflam: a new cellulose-biosynthesis-inhibiting herbicide provides long-term control of invasive winter annual grasses. *Pest Management Science* 73:2149-2162.

Sebastian, D. J., S. J. Nissen, J. R. Sebastian, and K. G. Beck. 2017b. Seed bank depletion: the key to long-term downy brome (*Bromus tectorum* L.) management. *Rangeland Ecology & Management* 70:477-483.

Sebastian, D. J., S. J. Nissen, J. R. Sebastian, P. J. Meiman, and K. G. Beck. 2017c. Preemergence control of nine invasive weeds with aminocyclopyrachlor, aminopyralid, and indaziflam. *Invasive Plant Science and Management* 10:99-109.

Sebastian, D. J., J. R. Sebastian, S. J. Nissen, and K. G. Beck. 2016. A potential new herbicide for invasive annual grass control on rangeland. *Rangeland Ecology & Management* 69:195-198.

Shaner, D. L. 2014. Herbicide Handbook. Weed Science Society of America.

Sheley, R. L., M.F. Carpinelli, and K.J. Reever Morghan. 2007. Effects of imazapic on target and nontarget vegetation during revegetation. *Weed Technology* 21:1071-1081.

Shinn, S. L., and D. C. Thill. 2004. Tolerance of several perennial grasses to imazapic. *Weed Technology*:60-65.

Wallace, J. M., and T. S. Prather. 2016. Herbicide control strategies for Ventenata dubia in the Intermountain Pacific Northwest. *Invasive Plant Science and Management* 9:128-137.

Whisenant, S. G., and D. W. Uresk. 1990. Spring burning Japanese brome in a western wheatgrass community. *Rangeland Ecology & Management/Journal of Range Management Archives* 43:205-208.

Wright, H. A., and J. O. Klemmedson. 1965. Effect of fire on bunchgrasses of the sagebrush-grass region in southern Idaho. *Ecology* 46:680-688.

Young, J. A., and F. L. Allen. 1997. Cheatgrass and range science: 1930-1950. *Rangeland Ecology & Management/Journal of Range Management Archives* 50:530-535.

Young, J. A., R. A. Evans, and R. A. Weaver. 1976. Estimating potential downy brome competition after wildfires. *Rangeland Ecology & Management/Journal of Range Management Archives* 29:322-325.

APPENDICES

Appendix A. Site-Specific Recommendations Summaries

<u>Sites Categorized as Level 1/Blue</u>

There are fewer land types that fall under the Level 1 category. These sites are mostly located in the shortgrass prairie landscapes, further away from airport facilities. These sites must be kept intact to prevent future weed invasions.

1. Assess site conditions to identify weed spectrum and desirable vegetation. These sites should have >75% desirable grass cover and minimal weed infestations. Downy brome, Russian knapweed, common mullein, and thistle species will likely be the most common species found in these less disturbed sites. White top may occur in riparian corridors.
2. Weed control and mowing needs will be a lower priority in these sites, however, they are still necessary to keep sites intact and keep weed invasions out.
3. A single herbicide application of <u>Esplanade + Method</u> will control the weed spectrum described above. Similar to sites categorized as Level 2, this application will provide effect long-term control.
    a. Apply any time throughout the year but include a post-emergent herbicide to control actively growing weeds. This may include glyphosate, 2,4-D, dicamba, or Vista. Only apply glyphosate when perennial grasses are dormant (late-September to early-March).
    b. Include Telar in areas where common mullein is present.
    c. <u>Riparian corridors:</u>

i. These areas will likely have more perennial weed species present, including white top. Include Telar to control white top and Russian knapweed – if treating white top, apply in May when plants are flowering
ii. Esplanade + Method + Telar can be applied up to water's edge. Do not apply directly to water if present.

d. **Weed Management Methods: Selective Weed Control** outlines application rates and timing and best management practices for using these herbicides.

Sites Categorized as Level 2/Yellow:

Land types that fall under this category are located across the entire airport property, from Pena Boulevard and the airfield, to riparian corridors and shortgrass prairie landscapes. Recommendations provided will be addressed to all areas unless otherwise specified.

1. Assess site conditions for present weed spectrum and desirable vegetation. Sites should have 25-75% desirable grass cover with moderate to high weed infestations. Remnant grass communities are essential for restoring these areas and are a key factor for managing these sites.
2. Weed control will be the first and most important management step in these areas. The most common weeds encountered include downy brome, kochia, field bindweed, Canada thistle, musk thistle, Russian knapweed, and white top, which occurs in most riparian corridors.
   a. Esplanade + Method is the recommended treatment for all sites across DEN property. It will control the large weed spectrum described above. This treatment will provide at least 2 years of control for downy brome and kochia.

b. Apply throughout the year but include a post-emergent herbicide to control actively growing weeds. This includes glyphosate, 2,4-D, dicamba, or Vista. Only apply glyphosate when perennial grasses are dormant (late-September to early-March).

c. Riparian corridors:

   i. These areas will likely have more perennial weed species present, including white top. Include Telar to control white top and Russian knapweed – if treating white top, apply in May when plants are flowering

   ii. Esplanade + Method + Telar can be applied up to water's edge. Do not apply directly to water if present.

d. **Weed Management Methods: Selective Weed Control** outlines application rates and timing and best management practices for using these herbicides.

e. The 3-point hitch boom sprayer should be used for most applications in these areas. UTV or pickup units should be used to spray narrow roadsides or smaller areas <1 acre in size.

   i. Before applying herbicides, always calibrate the spray unit for accurate and safe applications.

   ii. For steps on how to calibrate, mix, and handle herbicides, go to **Appendix D: Sprayer Calibration**.

f. **Always reference the herbicide label for application information and restrictions.**

3. Monitor sites and provide adaptive weed management for at least 2-3 years until weed infestations are greatly reduced or no longer a problem.

a. Monitor at least 2-3 times during the growing season. Monitoring frequency will depend on the site, annual precipitation, and the weed spectrum.
b. Kochia will likely come back into these perennial grass systems the first and second year after initial treatments, even after using Esplanade + Method. Apply Vista in the spring or summer before kochia plants are >8 inches tall. Apply dicamba in the summer if plants are >8 inches tall. **Appendix J** provides more information for using these herbicides to control kochia.

4. Roadsides and rights-of-way on landside and the airfield will need to be mowed to meet CDOT and FAA requirements. Mowing must be kept to a minimum throughout the year in these areas to promote healthy, sustainable grass communities. Focus mowing operations on maintaining vegetation height rather than weed control. Selective herbicide weed control should always be the first management method used when addressing weeds.
   a. Landside mowing:
      i. Keep mowing to one or two annual cuttings to manage vegetation height.
      ii. Do not mow during the peak perennial grass growing season (April – September). Mow at the end of the growing season once grasses have produced and dispersed seed (October-March).
      iii. Mowing heights should be kept at least 8 inches or higher.
      iv. Avoid mowing the entire right-of-way width. Reduce mowing swaths to only 6-12 feet from roadside.
   b. Airfield mowing:
      i. Keep mowing to one annual cutting to manage vegetation height.

ii. Mowing heights should be kept at least 6 inches or higher.

iii. Perform mowing practices early in the spring (early-March), or late fall (October to late-November) to reduce plant stress.

c. **Weed Management Methods: Mowing Operations** and **Appendix E** provides detailed information about best mowing practices and timings.

Sites categorized as Level 3/Red:

These areas are mostly located along Pena Boulevard, while some will be located around airport facilities and the airfield. These sites will either be reseeded with desirable grasses or left as bare ground. Airfield specific recommendations will be described in the summary to differentiate from the landside areas. Recommendations for bare ground should be used in areas where bare ground is required or desired, such as oil and gas wells, railroads, around roadside delineators, etc. More information for bare ground management can be found in **Sites Categorized as Bare Ground**.

Key management recommendations for sites with high weed infestations and <25% desirable grass cover.

1. Assess site conditions for weed species spectrum, if any desirable species are present, or if prairie dog colonies are present. Most common weeds that will occur in these sites include downy brome, kochia, field bindweed, flixweed, and prickly lettuce. Some of the highly degraded sites will be monocultures of kochia or field bindweed.
2. Remove weed species before taking further steps. Reference **Weed Management Methods: Selective Weed Control** for herbicide options based on the weed spectrum on site.

a. For revegetation projects, take soil samples to determine soil conditions and if seeding is possible. Use non-residual herbicides or short-term residual herbicides to control weeds. Apply 2-3 times throughout the spring and summer to control annual weeds. For seeding to be successful, prairie dogs must be removed from the site to allow for grass establishment.
b. For bare ground sites, use long-term, soil residual herbicides that provide at least one year of weed control. Apply in the fall for most effective control. Reference **Appendix L** for more information about bare ground applications.
c. Do not mow weeds unless plant heights are >12 inches. On the airfield, mow weeds only if plant heights are >6 inches tall. Mow earlier in the growing season before plants produce seed. Always include herbicide control with mowing to control weeds for the next season.

3. Continue to monitor sites for new weed growth in revegetation and bare ground sites during the spring and summer months.
    a. Keep revegetation sites weed free throughout the summer before seeding in the fall. **Selecting Desirable Grass Species and Seeding Rates: Seeding and Weed Control** and **Appendix I** provide more information about herbicides to use based on the weed spectrum and application timings for adaptive management.
    b. Bare ground sites will need follow-up herbicide applications every year, or every other year depending on the herbicides used, the weed spectrum, and annual precipitation.
4. <u>Seed desirable grasses in the fall</u> of the same year. Use one of the recommended seed mixes provided in **Appendix I**, depending on soil characteristics. Supplemental irrigation

should be provided for sites where it is accessible. Crested wheatgrass should be seeded in sites that need rapid establishment, soil stabilization, and may have poor soil and no irrigation. For more information about seed mixes and grass establishment, reference the **Selecting Desirable Grass Species and Seeding Rates** section.

5. Monitoring and adaptive weed management the following two seasons after seeding will be required for grass establishment.
    a. First growing season after seeding - apply glyphosate and other broadleaf herbicides to control kochia, downy brome, and other summer annual weeds; only apply glyphosate if seedling grasses have not emerged
    b. Apply broadleaf selective herbicides in combination with Esplanade and Method once seeded grasses have reached the 2-3 tiller stage.
    c. **Selecting Desirable Grass Species and Seed Rates** and **Appendix I** provides more information for adaptive weed management in seeding projects. Specific herbicides and application timings are provided here for the most common weeds at DEN.

Sites Categorized as Bare Ground

Bare ground sites should be considered as their own category. The goals associated with these sites are different than the other three categories and should be treated as so. Total vegetation control/bare ground will be necessary for a variety of different areas across the airport property. Keeping oil and gas well pads, fence lines, roadside delineators, etc. vegetation free will increase overall safety.

1. Assess site conditions to identify the weed spectrum and other vegetation present. Take note if desirable trees and/or shrubs are near the site being treated, this will influence the herbicides that can be used.
2. Bare ground treatments should be made in the fall to achieve season long control the following spring/summer. **Appendix L** provides specific treatments to apply in areas with different weed spectrums.
   a. Plainview SC will be the most effective treatment as it controls all vegetation present, including perennial grasses.
   b. If perennial grasses are not present, Esplanade (7 oz) + Method (10 oz) can be used to control most of the problematic weed species found at DEN.
   c. Add glyphosate to treatments to control any growing weeds at the time of application. This will include treatments made in the fall, spring, or summer.
   d. Use a selective bare ground treatment in sites that have desirable trees and/or shrubs. These species are sensitive to Method and Imazapyr. Appendix L specifies other treatments that will provide sensitive bare ground control that will not harm these species. **ALWAYS READ THE LABEL FOR ANY IMPLICATIONS REGARDING POTENTIAL RISK TO OTHER PLANT SPECIES.**
3. Recommended bare ground treatments will provide at least one season of weed control. Follow-up applications of the same treatment should be applied the following fall if weeds start to come back during the growing season. These sites will require monitoring throughout the growing season.

4. For more information about treatments, prices, weeds controlled, and application timings, refer to **Appendix L**.

DEN Herbicide Application Timing Matrix

	January	February	March	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.
kochia	Red	Red	Green	Green	Green	Red	Red	Red	Yellow	Green	Green	Red
downy brome	Green	Green	Yellow	Yellow	Yellow	Green	Green	Yellow	Green	Green	Green	Green
Japanese brome	Green	Green	Yellow	Yellow	Yellow	Green	Green	Yellow	Green	Green	Green	Green
field bindweed	Red	Red	Yellow	Green	Green	Green	Red	Red	Green	Green	Yellow	Red
curly dock	Red	Red	Green	Green	Red	Red	Red	Red	Yellow	Yellow	Yellow	Red
common mullein	Green	Green	Green	Green	Red	Red	Red	Red	Green	Green	Green	Green
hoary cress	Red	Red	Yellow	Green	Green	Green	Red	Red	Red	Red	Red	Red
Russian knapweed	Red	Red	Red	Green	Green	Green	Yellow	Yellow	Green	Green	Green	Green
Canada thistle	Red	Red	Yellow	Green	Green	Green	Yellow	Yellow	Green	Green	Green	Red
musk thistle	Red	Red	Yellow	Green	Green	Green	Yellow	Yellow	Green	Green	Green	Red
Scotch thistle	Red	Red	Yellow	Green	Green	Green	Yellow	Yellow	Green	Green	Green	Red

Legend:

Green	**Ideal Timing**	
Yellow	**Less effective**	
Red	**Do not apply**	

Figure B1. Recommended herbicide application timings for individual weed species. Green indicates the optimal time for herbicide treatment; yellow indicates effective, but less ideal time to treat; red indicates do not apply. Refer to the *Denver International Airport Weed Identification and Management Guide* to help find which herbicides to use when treating for each species.

Appendix C. Denver International Airport Weed Identification and Management Guide
Denver International Airport Weed Identification and Management Guide – Separate document

Appendix D. CSU Pena Boulevard Replicated Studies

Based on previous research conducted by CSU faculty and graduate students, we established two replicated research/demonstration plots at DEN. The purpose was to demonstrate the positive impacts of site-specific weed management to interested DEN groups. We selected sites with significant weed infestations that also had remnant perennial grass communities. The two sites were selected along Pena Boulevard for ease of access. The first site was located north of the Pikes Peak parking lot. This site was dominated by downy brome and kochia. Alkali sacaton, western wheatgrass, and inland saltgrass were also present. The second site was located west of Tower Road, in the median between west and eastbound Pena Boulevard. This site was also dominated with downy brome and kochia. Research plots were 20 feet wide and 30 feet long. Seven different herbicide treatments (Table D1) were applied in these plots and replicated four times at each site. Treatments were applied in June 2018 and field evaluations were conducted in July 2019 and 2020.

Table D1. Herbicides and rates applied in evaluating downy brome and kochia control and perennial grass response at two sites along Pena Boulevard.

Treatment Number	Herbicide Treatment	Rates (oz product/ac)
1	Non-treated control	N/A
2	Esplanade + Raptor + Method + Vista	5 + 6 + 8 + 12
3	Esplanade + Raptor + Piper + Vista	5 + 6 + 10 + 12
4	Esplanade + Raptor + Portfolio + Zidua + Vista	5 + 6 + 8 + 5 + 12
5	Esplanade + Method + Vista	5 + 8 + 12
6	Esplanade + Piper + Vista	5 + 10 + 12
7	Esplanade + Porfolio + Zidua + Vista	5 + 8 + 5 + 12

To determine herbicide impacts on downy brome and perennial grasses, both cover and biomass data were collected. Downy brome cover was significantly reduced in 2019 and 2020 at both locations. In year 2, all treatments with Esplanade had significantly less downy brome cover (75% cover versus 0% to 2% cover) compared to the non-treated control (Figure D1). Esplanade provides long-term residual control necessary for depleting downy brome from the soil seed bank, eliminating the need for annual herbicide applications. Further, this approach could reduce labor and herbicide costs compared to other herbicides that need to be applied annually.

At the beginning of this study, both sites had remnant grass communities; however, these grasses were being suppressed due to downy brome utilizing moisture early in the season before perennial grasses came out of winter dormancy. Once the downy brome was removed, desirable grasses responded positively to reduced weed competition. Perennial grass biomass increased significantly in 2019 and 2020 (Figure D2 and D3). In 2019 and 2020, perennial grass biomass resulted in a 2- to 3-fold and 5- to 10-fold increase, respectively, when compared to the non-treated control. At the Pikes Peak site, alkali sacaton, a warm season bunchgrass, is the dominant grass. The increased biomass from 2019 to 2020 was due to reduced downy brome competition and increased access to more resources. At the Tower Road site, western wheatgrass was the dominant species. In 2020, herbicide treated plots produced 5- to 10-fold more grass biomass than the weedy check plots; however, overall biomass was 41% lower compared to 2019 (Figure D2). The reduced biomass was due to a much drier spring in 2020 compared to 2019. In 2019, March to May precipitation was 5.87 inches, 3.23 inches of that came in May, while in 2020, over the same time frame, precipitation was 3.45 inches, with only 1.65 inches coming in May (Western Regional Climate Center 2020). Downy brome cover was over 80% in the non-treated plots resulting in very limited perennial grass productivity. This shows the impact that downy brome has on perennial grass sustainability. If forced to compete year after year with downy brome, there is the risk that desirable grasses would not survive. This is especially true in dry years or prolonged drought like Colorado experienced from 2001-2009 (National Integrated Drought Information System 2020). Northeastern Colorado is typically a very dry and arid environment; precipitation events can be inconsistent each year. This study shows how important adequate moisture is to have healthy stands of grass. It also shows the importance of removing downy brome and other weeds to allow for those grasses to recover overtime and develop a stronger, more resilient ecosystem that is sustainable in drier years.

At both locations, kochia cover was variable between replications in 2019 and 2020. In 2019, there was no statistical difference in kochia cover among treated and non-treated plots. Kochia cover was low at both sites, making it difficult to determine treatment effects. In 2020, kochia cover increased in all plots, including the non-treated control at both locations (Figure D4). Between the first and second year, there was an average increase in cover of ~20% between both sites. Although there was great natural variability in cover at both sites, none of the treatments successfully controlled kochia 2 YAT. The Esplanade + Method treatment was expected to provide at least 2 years of control; however, it did not provide the desired control past the first year. This study provided necessary information for making herbicide product and rate recommendations for DEN. Due to the lack of kochia control two seasons after treatment, higher rates of Esplanade and Method (7 oz/ac and 10 oz/ac, respectively) are recommended to extend kochia control. In addition, for situations where kochia does come back after one or two years, post-emergent herbicides will need to be applied when kochia is 2-4 inches tall, before it produces seed.

This study illustrated that sites invaded by weeds that have remnant grass populations can respond positively with timely weed management. Removing the downy brome for multiple years released the remnant perennial grass, increasing cover and biomass. These sites are now more resilient and resistant to future invasions (Chambers et al. 2014). There are sites at DEN where weed management may not result in the re-establishment of remnant grass communities. This will most likely be due to the fact that very few remnant grasses remain. Monitoring must be done in these sites to evaluate their response in following years, while also providing adaptive weed management. In addition, these sites may meet the specifications for reseeding once the weeds have been successfully removed for multiple years.

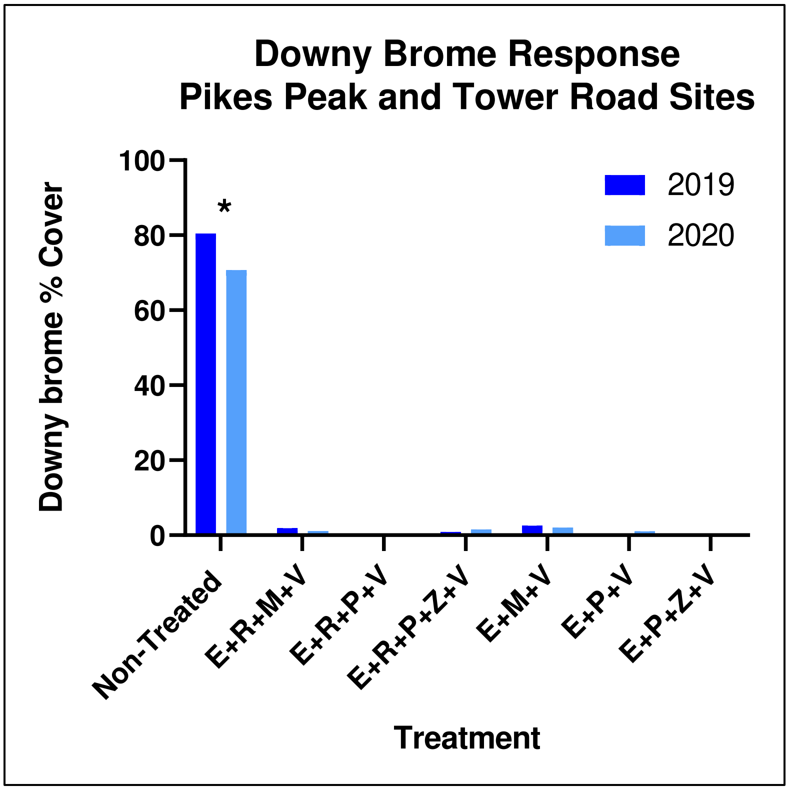


Figure D1. Downy brome cover combined for both sites, Pikes Peak and Tower Road, in 2019 and 2020. Asterisk indicates significant difference between non-treated control and treatments. Treatments include: Non-treated check; E+R+M+V (Esplanade + Raptor + Method + Vista); E+R+P+V (Esplanade + Raptor + Piper + Vista); E+R+P+Z+V (Esplanade + Raptor + Portfolio + Zidua + Vista); E+M+V (Esplanade + Method + Vista); E+P+V (Esplanade + Piper + Vista); and E+P+Z+V (Esplanade + Portfolio + Zidua + Vista).

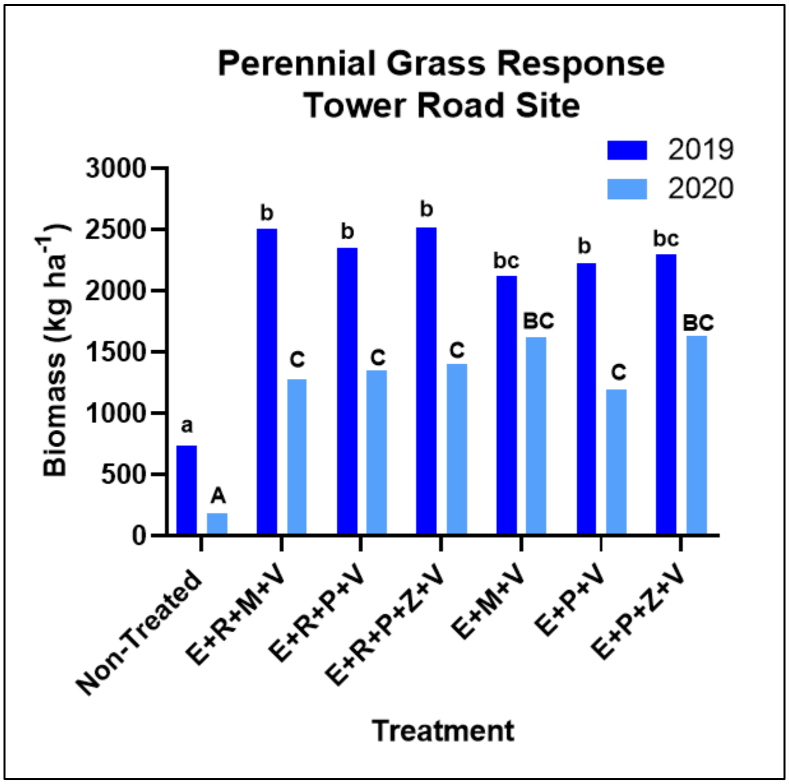


Figure D2. Perennial grass biomass response at the Tower Road site in 2019 and 2020. Letters indicate significant differences among treatments across both years. Treatments include: Non-treated check; E+R+M+V (Esplanade + Raptor + Method + Vista); E+R+P+V (Esplanade + Raptor + Piper + Vista); E+R+P+Z+V (Esplanade + Raptor + Portfolio + Zidua + Vista); E+M+V (Esplanade + Method + Vista); E+P+V (Esplanade + Piper + Vista); and E+P+Z+V (Esplanade + Portfolio + Zidua + Vista).

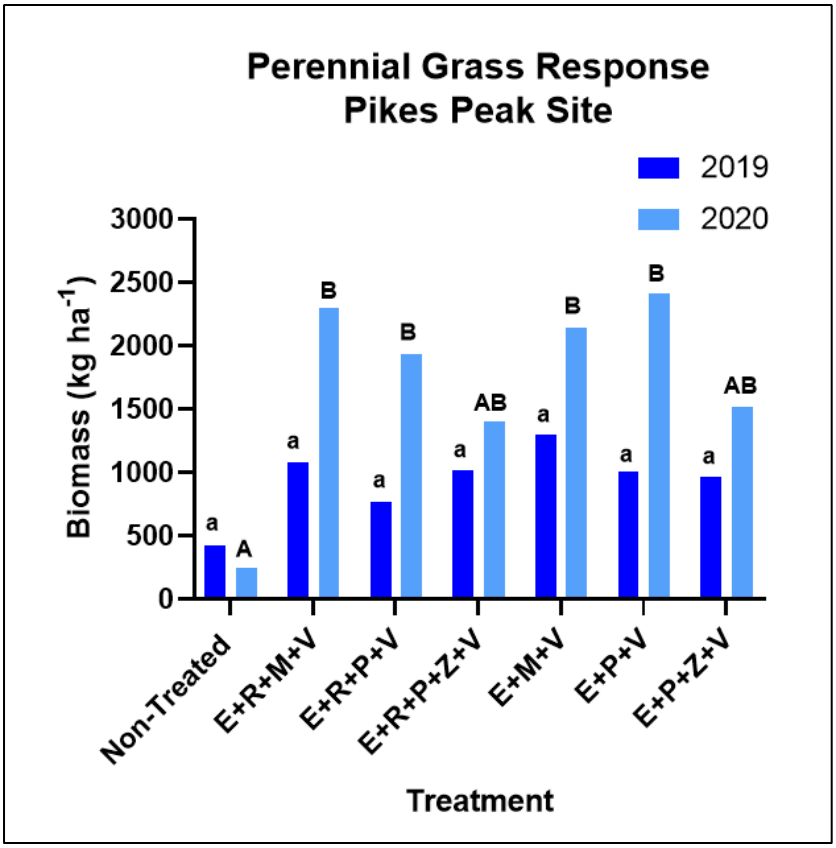


Figure D3. Perennial grass biomass (kg ha^{-1}) at the Pikes Peak site. Biomass response to treatments are shown for 2019 and 2020. Letters indicate significant differences among treatments across both years. Treatments include: Non-treated check; E+R+M+V (Esplanade + Raptor + Method + Vista); E+R+P+V (Esplanade + Raptor + Piper + Vista); E+R+P+Z+V (Esplanade + Raptor + Portfolio + Zidua + Vista); E+M+V (Esplanade + Method + Vista); E+P+V (Esplanade + Piper + Vista); and E+P+Z+V (Esplanade + Portfolio + Zidua + Vista).

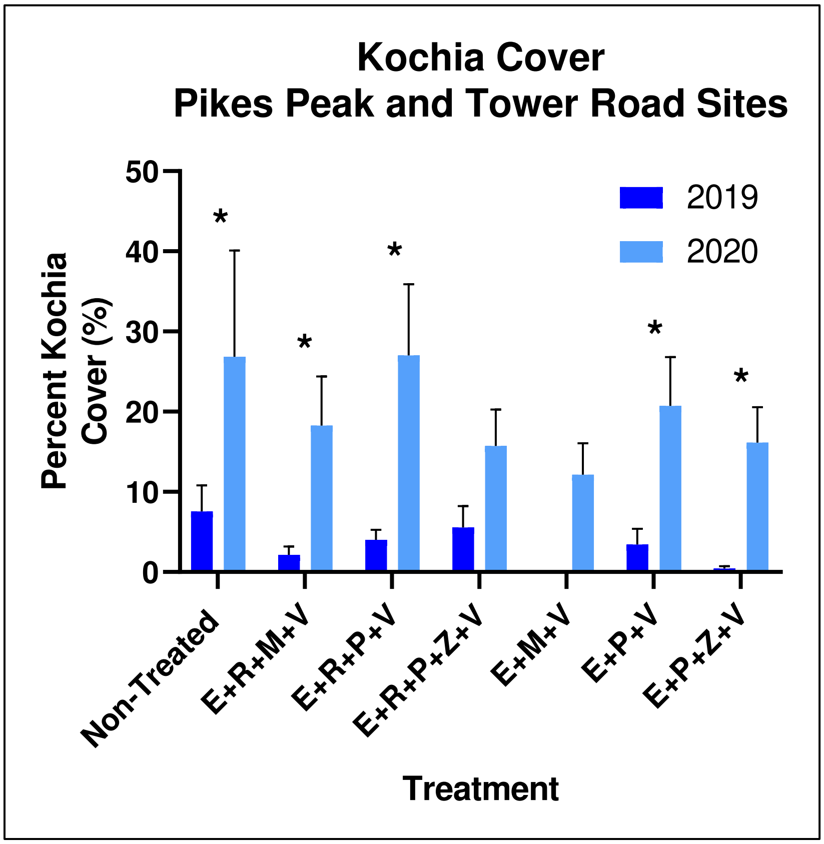


Figure D4. Kochia cover at both Pikes Peak and Tower Road sites in 2019 and 2020. Standard error bars represent variability for each treatment across each replicated treatment. Asterisk indicates significant increase in kochia cover from year 1 to year 2. Treatments include: Non-treated check; E+R+M+V (Esplanade + Raptor + Method + Vista); E+R+P+V (Esplanade + Raptor + Piper + Vista); E+R+P+Z+V (Esplanade + Raptor + Portfolio + Zidua + Vista); E+M+V (Esplanade + Method + Vista); E+P+V (Esplanade + Piper + Vista); and E+P+Z+V (Esplanade + Portfolio + Zidua + Vista).

Appendix E. Sprayer Calibration
General Considerations:

Three factors effect sprayer output (gallons of treatment solution applied per acre, GPA): nozzle output (gallons per minute (GPM)), boom width (feet), and ground speed (mph).

1. Selecting the proper nozzle for an application is important for good herbicide coverage and performance. The spray nozzle determines the amount of herbicide applied per acre, the application uniformity, the size of the spray droplets, and the potential for off-target movement (also known as spray drift).

   Nozzles for Boom Sprayer: We recommended that DEN use the TeeJet AIXR 11003 nozzle for their 3-point hitch sprayer. This is an air induction, flat fan nozzle (Figure E1). The 110° wide angle provides better drift management using the air induction technology. Using an air induction nozzle increases the droplet size that reduces the potential for drift to occur compared to a nozzle with a finer droplet size. Medium coarse droplet are also so recommended for pre-emergent herbicides, as well as herbicides that are absorbed and transported through the whole plant (TeeJet Technologies 2013). Many of the herbicides recommended for DEN fall under these two categories.

   The wider angle also allows for the boom to be closer to the ground, increasing uniform coverage on the target plants and further reduces drift potential. The nozzle output capacity is 30 gallons per acre (GPA). Herbicide applications should be made at 20 GPA; however, a 30 GPA nozzle allows for the sprayer to travel at a faster speed to achieve a 20 GPA application rate.

Figure E1. TeeJet AIXR 11003 air induction, flat fan nozzle (110 is the wide flat spray angle; 03 represents 0.3 gallons delivered per minute). This spray nozzle is recommended for DEN to use on their 3-point hitch sprayer.

Boomless sprayer nozzles: Boomless nozzles are used for areas where it is not practical to access with the large 3-point hitch sprayer. DEN UTV and truck units should be equipped with the boomless nozzles to access areas with rougher terrain, narrow roadsides, etc. We recommended that DEN use the Hypro Boom X-Tender nozzle - XT020 (Figure E2). These nozzles spray laterally at distances up to 20 feet, so combining two nozzles spraying in opposite directions creates a wide spray pattern. The recommended nozzle delivers 20 GPA and the pressure should be set at 40 PSI. Although these nozzles are a good alternative for the settings discussed earlier, there are inconsistencies in the spray pattern that lead to inconsistent and poor coverage. Better coverage is often achieved for lower vegetation.

Figure E2. Hypro X-Tender boomless spray nozzle delivers 20 GPM at 40 PSI.

2. Boom width and nozzle spacing will not change. Nozzle spacing on the 3-point hitch boom is 20 inches apart. The effective spray width of the boom will also not change. This is the effective width of the spray pattern.
3. Accurate and consistent ground speed is critical for herbicide applications. The application rate is most often determined by the combination of nozzle output and ground speed. Pressure is kept constant within the operating range of the nozzles, usually 30-40 PSI. Pressures below 30 PSI may not produce the full 110° nozzle pattern, so the spray pattern will not be uniform. Pressure above 40 PSI will produce more fine particles that can cause off-target drift.

Sprayer Calibration Methods

Frequent calibration should be done throughout the spraying season to check that all nozzles are working properly, the pressure is staying consistent, and that the overall unit is functioning within manufacturers specifications.

For each calibration method a tape measure, a stopwatch, flags, volumetric measuring containers (mL or oz), and paper to do calculations will be needed.

3-Point Hitch Boom Sprayer: 1/128 of an Acre Method

1. Clean and fill the spray tank half full of water.
2. Check the herbicide label to determine the gallons per acre (i.e. 20 GPA) needed to achieve a uniform application.

3. Turn spray system on to check for leaks, nozzle output, and spray pattern. If the spray pattern is not uniform or a nozzle is not putting out any water, check the screen and the nozzle for an obstruction. Rinse the screen in clean water and use a soft-bristle brush to remove any material from the nozzle tip. The TeeJet XR 11003 nozzles can be cleaned by removing the pre-orifice from the nozzle body (Figure E3 (TeeJet Technologies 2013)). If the nozzle is clean, you should be able to see light through the nozzle body.

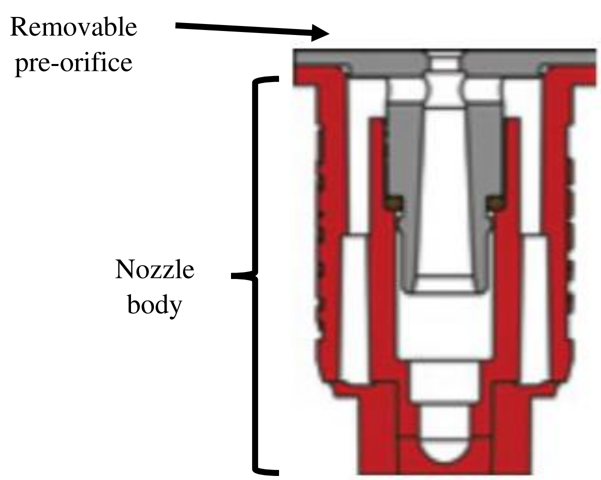


Figure E3. TeeJet XR 11003 nozzle body. The grey colored part of the nozzle is the pre-orifice that can be pulled out of the nozzle body. To clean the nozzle, use a soft brush to clean the tip of the nozzle body and pre-orifice.

4. Measure the distance in inches between the nozzles*. The John Deere LS1130 model has 20-inch nozzle spacings. Based off the 20-inch spacing (1.67 ft), a linear distance of 204 feet should be marked off. The nozzle spacing and linear distance represent the area that must be traveled to spray 1/128 of an acre (1.67 ft * 204 ft = 340 ft). One nozzle will cover 1/128 of an acre and the output collected (in ounces) in the time it takes to travel the 204 feet (1/128 of an acre) will directly convert to gallons sprayed over one acre.

$$\frac{43{,}560\ ft^2}{acre} \div 128\ = 340\ ft^2$$

5. Travel the 204 feet at a regular spraying speed (i.e. 4-5 mph). To achieve a 20 GPA application rate, you should travel at 4.5 mph. If you were to travel at a slower speed (i.e. 3.5 mph) with nozzle size and pressure held constant, the application rate would increase. If you were to travel at 5.5 mph, with nozzle size and pressure held constant, the application rate would decrease.

   Drive through the measured distance and record the time it takes to travel from the start to the end in seconds. Repeat this step at least two times for better accuracy; average the timings.

6. Park the sprayer and determine nozzle output by collecting the output from each nozzle with a measuring cup (graduated in ounces) for the same amount of time it took to travel the measured distance in step 5.

7. To determine nozzle output, add each of the nozzle outputs together and then divide by the total number of nozzles. If an individual nozzle output is 5% lower or higher (error range) from the average, check for blockages, clean the tip or replace the nozzle. Nozzles do ware out over time and this increases the spray output because the orifice can increase in size. The steps provided below should be repeated until all nozzles fall under the error range.

   i. To check the output of the nozzles, average the output from each nozzle on the boom and divide by the total number of nozzles:

   $$\frac{nozzle\ 1\ output + nozzle\ 2\ output + etc.}{number\ of\ nozzles\ on\ boom} = average\ nozzle\ output$$

   ii. Average nozzle output * 0.05 = amount to add or subtract from the average nozzle output to make an error range of 5%

iii. If the nozzle output of a single nozzle falls outside of the error range, it must be cleaned or replaced.

- Example scenario for when nozzle output falls outside of the error range.

Nozzle	Output (oz)
1	44
2	42
3	47
4	43

1. Average nozzle output

$$\frac{44 + 42 + 47 + 43}{4\, nozzles} = 44.25\, oz$$

2. 44.25 oz * 0.05 = 2.2 oz to add or subtract from the average

3. 44.25 oz – 2.2 oz = 42.05 oz

   44.25 oz + 2.2 oz = 46.45 oz

   Error range = 42.05 oz to 46.45 oz

4. Nozzle 3 is applying more output compared to the other three nozzles. It should be cleaned or replaced because it falls outside of the error range.

- Example scenario for when all nozzles are within the error range.

Nozzle	Output (oz)
1	41
2	42
3	42
4	43

1. Average nozzle output

$$\frac{41 + 42 + 42 + 43}{4\, nozzles} = 42\, oz$$

2. 42 oz * 0.05 = 2.1 oz to add or subtract from the average

3. 42 oz – 2.1oz = 39.9 oz

42 oz + 2.1 oz = 44.1 oz

Error range = 39.9 oz to 44.1 oz

4. Each nozzle falls within the error range; therefore, they are applying roughly the same output.

8. Once all nozzles are within the error range, collect the spray from a single nozzle in ounces for the time it took to travel 204 feet. This step does not need to be repeated if all nozzles were initially within the error range. Because we have calculated the output to cover 1/128 of an acre, the amount of spray we collect is equal to the application rate in gallons per acre because there are 128 oz/gallon. Average nozzle output (ounces) = application rate (gallons per acre)
9. Check the calculated output rate to the recommended rate (20 GPA). If the calculated rate is more or less than 5% the recommended rate, make one of these adjustments:
    a. The first, and easiest, option is to adjust the ground speed.
    b. The second option would be to adjust the pressure.
    c. The third option would be to change the nozzle size.
10. Recalibrate if any adjustments were made.

*Distances for calibration are based off nozzle spacing and the concept of spraying 1/128 of an acre per nozzle. The convenient conversion from 128 ounces to 1 gallon directly relates to the application rate in gallons per acre. For example, if the average output is 19 ounces, the application rate is 19 gallons per acre. It does not matter how many nozzles you have; this calibration method will work. For other nozzle spacings, please refer to the Ohio State University Extension: Boom Sprayer Calibration resource(Ozkan 2016).

Refill Calibration Method for the UTV/Truck Sprayer

This method is useful for applications made with smaller tank volumes.

1. Clean and fill the spray tank completely full of water.
2. Using clean water, test the operating condition of the sprayer by simply charging the boom and identifying any issues. Check that all nozzles have a uniform pattern and the same output. If nozzles do not work, or the pattern is uniform, check that the nozzles are clean. If the output is low or the pattern is not in a fan shape, clean the nozzle with a soft-bristle brush (i.e. toothbrush).
3. Mark 100 feet on the ground using a tape measure and flags to allow the sprayer operator to know where to stop and stop spraying. Practice until you drive this distance at a constant speed. Traveling 100 feet in 23 seconds means that your speed is 4.3 mph, 17 seconds is 4 mph, and 13.6 seconds is 5 mph. Note that the precise speed is not as important as being consistent.
4. Completely refill the tank. Turn on the boom and spray the same amount of time it took you to travel 100 feet. Refill the tank to determine the volume of water used.
5. Carefully measure the gallons of water used by filling a volumetric container and refilling the tank until it reaches the reference line. A large container measured in ounces or gallons will be best for this. Repeat steps 3 and 4, two or three more times for more accurate calibration. Returning the sprayer to the same spot it was refilled will increase accuracy, too.
6. Determine the number of gallons needed to refill the tank based off the volumetric measurements. To calculate the spray rate in gallons per acre, use the boom width and the linear distance traveled. This number will give you a percentage of an acre, which is then

divided by the number of gallons it took to refill the tank, resulting in the GPA rate applied.

i. Boom width = 30 feet; distance traveled = 100 feet

$$30\ feet * 100\ feet = 3{,}000\ ft^2$$

ii. $\frac{3{,}000\ ft^2}{43{,}560\ ft^2} = 0.068\ acre$

iii. Use 0.068 of an acre to determine GPA by dividing the number of gallons it took to refill the tank by 0.068. For example, if it took 1.3 gallons to refill the tank, the application rate would be 19 GPA.

$$\frac{1.3\ gallons}{0.068\ acre} = 19.1\ GPA$$

Handgun Sprayer Calibration Procedure: Another version of 1/128 of an Acre Method

*The handgun should be used for spot treatments or weed infestations that are small and do not require a large boom sprayer to treat. Use the handgun attached to the three-point hitch boom sprayer.

The 1/128 of an acre method is based on the ratio of 1 gallon, or 128 oz, to $1/128^{th}$ of an acre. This is a fast and simple calibration method that requires no math. Results in ounces (oz) are directly converted to gallons per acre (GPA). (1 ounce = 1 gallon)

1. Measure and mark off an area of 18.5 ft by 18.5 ft (340 ft^2). This can be done using flags or spray paint.
2. Using the handgun, spray the area at a comfortable, consistent pace to get uniform coverage for the whole area. While doing this, use a stopwatch to measure the time it takes to cover the area. Repeat 2-3 more times to get an accurate spray time.

3. Spray the handgun into a bucket for the average time it took to spray the 18.5 ft by 18.5 ft ($340\ ft^2$) area.
4. Measure the amount of water in the bucket using a volumetric container in milliliters (mL) or ounces (oz).
5. The amount of water collected is the amount of water that it takes to spray 1/128 of an acre in the allotted time. If measured in ounces, this is a direct conversion to gallons per acre. If measured in milliliters, convert to ounces before converting to gallons.
   i. 68 ounces collected ⟶ the sprayer output is 68 gallons per acre (GPA)
   ii. 2,010 mL collected = 2,010 mL/29.57mL per oz = 68 oz or 68 gallons per acre (GPA)

<u>How much herbicide to add to the tank?</u>

It is important to accurately calculate and mix the appropriate amount of herbicide product needed for the weeds to be controlled. This makes for safe, effective, and legal applications. Always **CHECK THE HERBICIDE LABEL** for how to mix the product. Calculations will be necessary and will vary depending on the rate used, the gallons per acre applied, and the number of acres to be treated. Mixing and the amount of product needed will also depend on the type of herbicide being used. If several products are being mixed in the spray tank, there will be recommendations on the mixing order (see recommendations below).

The herbicide label will provide the recommended rate to be applied per acre but could vary by weed species. This may be in ounces, pints, quarts per acre). Most of the recommended products to be used at DEN will be liquid formulations measured in fluid ounces, although a few products will be dry formulations (i.e. granules, dry flowable) and will be measured out by weight in ounces. Below are a few different calculations for determining how much herbicide product to add to the spray tank.

Determine the amount of liquid product to add to a tank:

i. 300-gallon tank

ii. Calibrated to deliver 20 GPA

iii. Recommended rate for Esplanade is 5 fl oz/acre

a. $\frac{300\ gallon\ tank}{20\ GPA} = 15\ acres\ covered\ per\ tank$

b. $\frac{15\ acres}{tank} \times \frac{5\ fl\ oz\ Esplanade}{acre} = 75\ fl\ oz\ Esplanade\ per\ tank$

Determine the amount of dry product to add to a tank:

a. $\frac{300\ gallon\ tank}{20\ GPA} = 15\ acres\ covered\ per\ tank$

b. $\frac{15\ acres}{tank} \times \frac{1.5\ oz\ Telar}{acre} = 22.5\ oz\ Telar\ per\ tank$

Mixing and Handling Herbicide

When handling any herbicide, be sure to wear personal protection equipment (PPE). This includes gloves, eye protection, long sleeve shirts, pants, and closed toed shoes. Always reference the product label for required PPE when handling, mixing, or applying any product. There can be different PPE requirements for mixing and loading compared to what is required for the applicator.

Mixing herbicides can cause issues as some herbicides may not be compatible or need to be mixed with water before being combined with other herbicides. Therefore, it is important to follow a specific order to eliminate any problems.

Follow these steps to minimize any mixing issues:

1. Fill the tank 50% full of water. Turn on the agitator which can be found on the agitator valve on the LS1130 sprayer.
2. Always check the product label for compatibility issues and for specific mixing instructions. Labels will provide the information for each herbicide formulation.
3. Dry products must be added first. These will include wettable powders (WP), wettable granules (WG), or dry flowables (DF). Once these are added, allow enough time for the agitator to dissolve/mix them. These products can also be added to a small amount of water to create a slurry before being added to the tank. This allows for products to properly dissolve in water.
4. Liquid products are added next. This will include, but is not limited to, soluble concentrates (SC), soluble liquids (SL), or emulsifiable concentrates (EC).
5. Once all herbicide products are added to the tank, an adjuvant/surfactant must be added. Specifically, for any applications made to emerged plants. Nonionic surfactant (NIS) or methylated seed oil (MSO) are recommended most often.
6. The addition of de-foaming agents could be beneficial when mixing. During the mixing process, the tank agitator should be on to help mix the herbicides. This agitation can cause foaming, which can come out of

the top of the tank; therefore, adding a de-foaming agent to the tank can reduce foam production.

7. Fill the rest of the tank with water.

Appendix F. Recommended Mowing Times

Recommended Mowing Times

Mowing should be done only as needed. Focus mowing on managing vegetation heights for visibility rather than for weed control. Control weeds using selective herbicides and mow once a year for height management.

Do not mow newly seeded grasses for 2 to 3 years unless necessary. Keep mowing heights 8 inches or higher (Arizona Department of Transporation (ADOT) 2018).

	Jan	Feb	March	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Landside/Airfield Mowing	+	+	+	O	O	*	*	*	O	+	+	+

NOTES:

Yellow corresponds to warmest months of the year.

+ = best time to mow (mowing can be done if there is no snow or mud)

O = mowing is not recommended (plants are at most sensitive stage as they come out of winter dormancy)

*= mowing okay (only mow if necessary and adequate precipitation/moisture is available; consider wildlife hazard mitigation on airfield)

Appendix G. Alternative Mowing Option for DEN Rights-of-Way and Airfield

- Derigo – chemical mowing product used as an alternative to mechanical mowing on roadsides with guardrails, delineators, and along airfield runways
- Provides season long grass height and seed head suppression
- Applied in the early months of the growing season for cool and warm season grasses
    - Cool season: April timing
    - Warm season: mid-May to early-June timing
- Reduces the number of times grasses need to be mowed in a season, reduces wildlife attractions by suppressing seed head development, promotes healthier grass growth without the removal of aboveground vegetation via mowing
- Replaces or reduces mowing operations and risks to mowing operators and travelers
- Studies on crested wheatgrass, Western wheatgrass, and smooth brome have proven to be effective and cause no injury to grass
- Can be easily added to an herbicide tank mixes to control weeds and suppress grass height and seed head suppression
- Low field use rate (1 – 2 oz/acre)
    - 1 oz for Western wheatgrass and crested wheatgrass
    - 1.5 oz for smooth brome

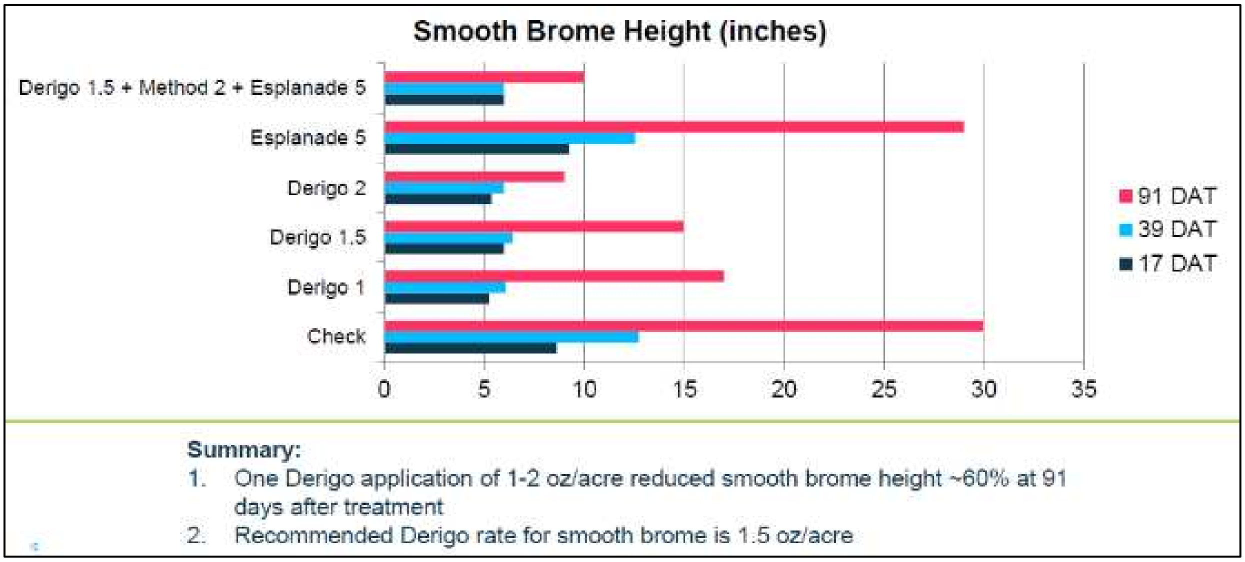


Figure G1. Smooth brome height suppression. Treatments made in April 2019.

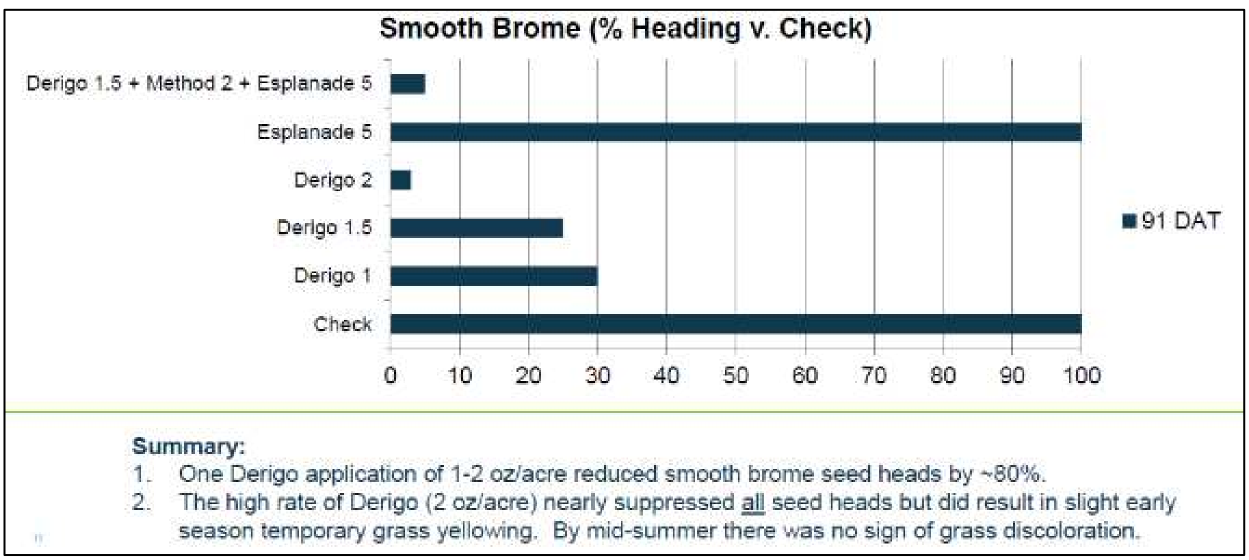


Figure G2. Smooth brome seed head suppression compared to the non-treated check. Treatments applied in April 2019.

Appendix H. GEOWEB Technology and Vegetation Establishment for Revegetation

Slope stabilization for erosion control is necessary to achieve healthy, stable slopes for vegetation growth. Observations made around the DEN airport facilities and roadsides indicates there are major soil stabilization issues. These issues range from deep gullies that cut through the hillsides to large washouts that move soil to the bottom of the hillsides. Roadsides with steep slopes and no desirable, supporting vegetation are very common at DEN and should be addressed. It is difficult to establish desirable grasses on these slopes as they are prone to water runoff and soil erosion that creates unstable soils, resulting in the problematic washouts or deep gullies.

One option to address these issues is to use the GEOWEB technology. This technology is used to create stable growing environments, by providing hillside stability, reducing surface runoff, and allowing for vegetation to grow. This material is composed of a honeycomb-like network of cells that have small holes in the sides to allow for roots to grow through. The GEOWEB material can withstand thousands of pounds pressure and can be driven over.

CSU partnered with DEN Field Maintenance and a GEOWEB distributor to establish two different demonstration plots on East 75th Avenue, near the DHL service building in April 2019. The goal was to demonstrate how this system would work in combination with revegetation methods for areas on DEN property with steep slopes and poor stabilization.

Two GEOWEB systems were installed in April 2019 (approximately 8’ x 25’). An area about this size was excavated to six inches deep so the material could be stretched down the slope and backfilled with topsoil once the material was stabilized. After filling each cell with enough soil to where they were filled (Figures H1 and H2), four different grass species were planted into the cells. Grass plugs were planted into individual cells on 2’ x 2’ centers to allow for enough space for grass roots to spread through the holes of the geocells (Figure H3). The purpose of the grasses is to provide deeper soil stabilization from the root systems, while the GEOWEB prevents surface runoff and erosion that could prevent the grasses from growing and soil washing out from around the plants. Four grass species, either bunch or sod-forming, were planted in late-April 2019. These included manystem wildrye, crested wheatgrass, inland saltgrass, and alkaligrass. Manystem wildrye spreads by underground stems and can form stands of sod that provide soil stabilization (Young-Matthews and Winslow 2010). Inland saltgrass is very similar, as it spreads by underground rhizomes (Skaradek and Miller 2010). DEN Field Maintenance provided supplemental irrigation at both sites using a 3000-gallon water truck and garden hose throughout the summer of 2019 and 2020. Over the course of the demonstration, both sites were monitored for weed invasion and grass growth. Fluroxypyr and 2,4-D were applied to control actively growing weeds.

In 2020, grass survival was evaluated for each species. Among the four grass species, three survived. Crested wheatgrass, inland saltgrass, and manystem wildrye successfully established and spread. Crested wheatgrass bunches grew taller and wider, while inland saltgrass and manystem wildrye both had new vegetation that spread from the parent plants. Inland saltgrass was more successful at spreading after one year compared to the manystem wildrye (Figure H4).

If the GEOWEB system is used in combination with revegetation via grass plugs in sites that require increased erosion control, it is suggested to use grasses that are known to spread quickly for fast soil stabilization. Other grasses that are known to successfully spread are Western wheatgrass and buffalograss. These were not included in the demonstration sites, but due to their rhizomatous and stoloniferous growth characteristics, they are likely to successfully spread with adequate moisture and weed control.

Figure H1. Black material is the GEOWEB system laid and stretched out along the side of the slope. Topsoil was dumped at the top of the slope to fill GEOWEB cells.

Figure H2. DEN Field Maintenance personnel moving the topsoil down the slope to fill GEOWEB cells.

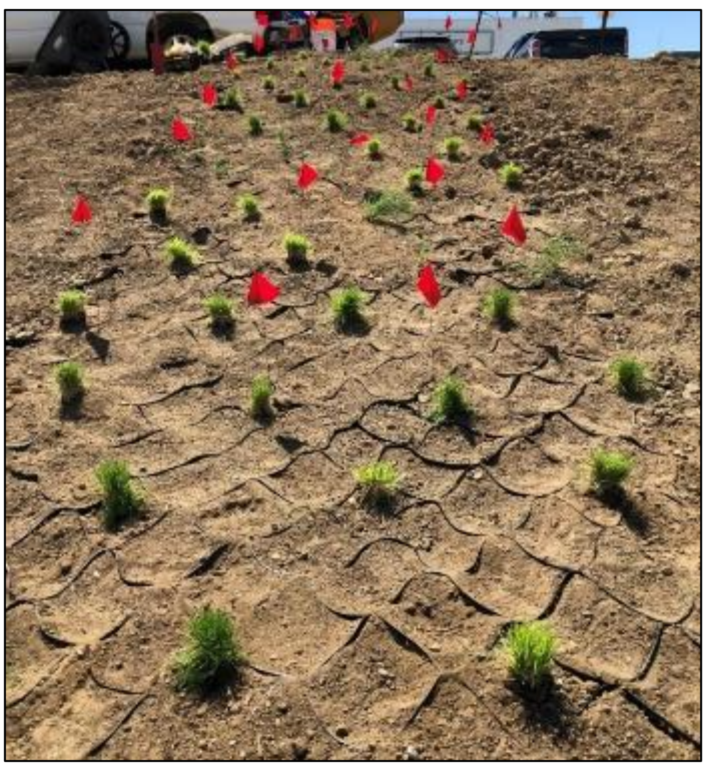


Figure H3. Four different grass species planted into GEOWEB cells. Grass species include manystem wildrye, crested wheatgrass, inland saltgrass, and alkaligrass. Picture taken day of planting in April 2019.

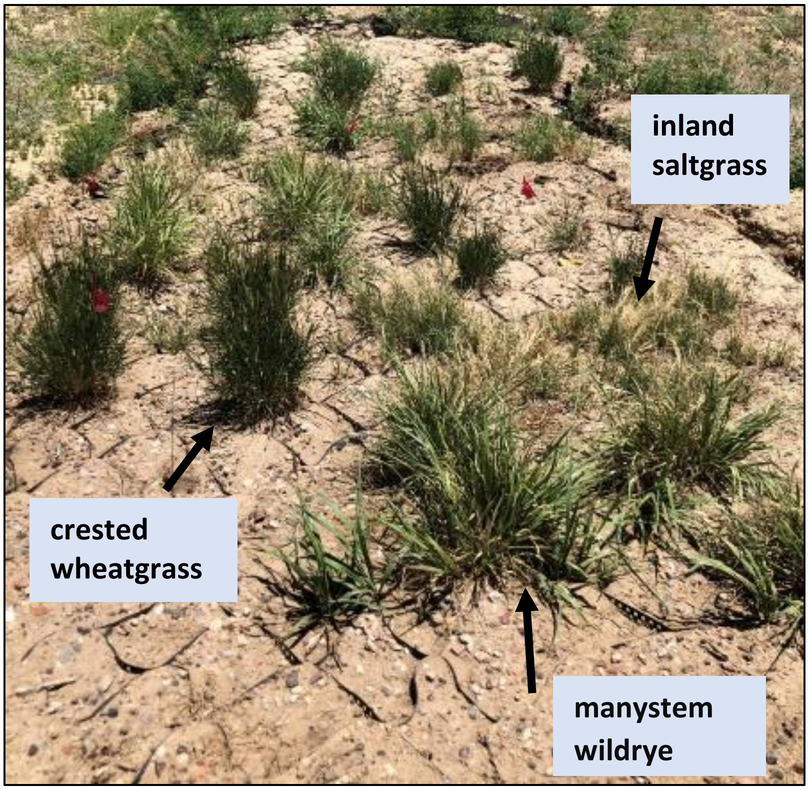


Figure H4. Established grasses in April 2020. Inland saltgrass, crested wheatgrass, and manystem wildrye were well-established. The alkaligrass did not survive. Observed vegetative spreading was observed in the manystem wildrye and inland saltgrass.

The same grass species were also planted into the replicated revegetation sites on East 75th Avenue and at the Tower Road site. Inland saltgrass, crested wheatgrass, and manystem wildrye had the greatest survival at the Tower Road site; however, only the crested wheatgrass and manystem wildrye were successful at the 75th Avenue site. From the observations made at both sites, it is recommended to utilize grass plugs in smaller areas that have access to water and soil conditions are less harsh.

Overall, grass plugs can and should be considered as a revegetation option for smaller areas that provide the option for erosion control, such as the GEOWEB, and have access to supplemental water. Crested wheatgrass, manystem wildrye, and inland saltgrass are a few options and can provide soil stability through vegetative spreading below and above the soil.

Appendix I. Grass Seed Mix Recommendations for AOA and Landside

Seeding mixes were developed with the help of Dr. Ken Lair, a former Plant Materials Specialist at the NRCS-USDA. Each mix is composed of desirable species that are commonly found in arid, dry environments like eastern Colorado. Some species can be difficult to establish without adequate moisture and should be utilized in sites that could provide supplemental irrigation, at least during the establishment year.

Always assess the project goals and necessity for soil stabilization and site conditions when choosing to use a seed mix or a monoculture stand of a fast establishing and persistent species. Costs per pound are based on Pawnee Buttes Seed Inc. in Greeley, CO. Prices may differ among seed distributors.

Table I1. Seeding mix recommendation for saline upland sites.

Dry/Upland Grass Mix -1 clay, clay loam, sandy clay loam - saline swale/bottomland					
Common Name	**Soil Adaptation**	**% of mix**	**PLS lbs/acre***	**Cost/lb**	**Cost/acre**
western wheatgrass	silt loam to clay loam	25	2.4	$ 4.75	$ 11.40
switchgrass	clay loam to sandy loam	15	0.4	$ 7.50	$ 3.00
crested wheatgrass	silt loam to clay loam	25	1	$ 3.95	$ 3.95
slender wheatgrass	loam to clay loam	15	1	$ 3.40	$ 3.40
Altai wildrye	loam to clay loam	10	1.5	$ 15.00	$ 22.50
alkali sacaton	loam to clay	10	0.06	$ 27.00	$ 1.62
Total		**100**	**6.36**		**$ 45.87**

Table I2. Seeding mix recommendation for upland non-saline land types.

Upland Grass Mix 2 - clay, clay loam, sandy clay loam – non-saline swale/bottomland					
Common Name	**Soil Adaptation**	**% of mix**	**PLS lbs/acre***	**Cost/lb**	**Cost/acre**
western wheatgrass	silt loam to clay loam	20	1.9	$ 4.75	$ 9.03
crested wheatgrass	silt loam to clay loam	20	0.8	$ 3.95	$ 3.16
switchgrass	clay loam to sandy loam	15	0.4	$ 7.50	$ 3.00
slender wheatgrass	loam to clay loam	15	1	$ 3.40	$ 3.40
blue grama	sandy loam to silt loam	15	0.2	$ 12.00	$ 2.40
creeping wildrye	silt loam to clay loam	15	1.1	$ 120.00	$ 132.00
Total		**100**	**6.2**		**$ 152.99**

Table I3. Seeding mix recommendation for wet/drainage sites.

Wet/Drainage Grass Mix					
Common Name	**Soil Adaptation**	**% of mix**	**PLS lb/acre****	**Cost/lb**	**Cost/acre**
switchgrass	clay loam to sandy loam	15	0.8	$ 7.50	$ 6.00
streambank wheatgrass	loam to clay loam	15	2.1	$ 6.75	$ 14.18
alkaligrass	clay loam to clay	15	0.3	$ 3.90	$ 1.17
western wheatgrass	Silt loam to clay loam	25	3.8	$ 4.75	$ 22.33
slender wheatgrass	loam to clay loam	20	2.7	$ 3.40	$ 9.18
Baltic rush	loam to clay loam	10	0.1	$ 250.00	$ 25.00
Total		**100**	**9.7**		**$ 77.85**

*Seeding rates are based off a drill-seeding rate of 25 seeds per square foot.

**PLS lb/acre rate based off 50 seeds per square foot. Because this mix is suited for wetter areas, the number of seeds can be increased with more moisture available.

Seeding rates are based on recommendations for dryland drill seedings. Rates are given in pounds of pure live seed (PLS) per acre. To calculate PLS pounds/acre, the number of seeds per square foot should be determined. For dryland drill seedings, 25-40 seeds per square foot are recommended. Planting more than 40 seeds/ft^2 is not ecologically or economically desirable. Higher seeding rates do not necessarily guarantee grass establishment. Seeding rates should be doubled if broadcast seeding. Always calibrate the rangeland drill, or broadcast seeder, before seeding to achieve desired seeding rates. Typically, single species and seed mix rates for grasses vary from 5-15 pounds per acre. These rates can vary depending on the seed size for each species included in the mixture. Comparing among large, fluffy, or small seeds in a mixture, larger and fluffy seeds have less seeds per pound (ex. Western wheatgrass (115,000 seeds/lb) and sideoats grama (191,000 seeds/lb), respectively), whereas smaller seeds (ex. inland saltgrass (518,000 seeds/lb) have more seeds per pound. Figure I1 illustrates the difference in seed size for the three seed types. Seeding rates should be given for all prescribed grass mixtures or single species when writing contract specifications.

To calculate the seeding rate for a species, the number of seeds per square foot, the number of seeds per pound, and the total number of seeds per acre must be known. If using a seed mix, the percentage of each grass in the mix should be established based on site characteristics and average rainfall. The known number of seeds per pound for a species can be found through various resources, including the Technical Note for *Plant Suitability and Seeding Rates for Conservation Plantings in Colorado* (Taliga 2011). The example below provides a step by step guide for how to calculate the seeding rate (PLS pounds/acre) for Western wheatgrass. A seeding rate is given for a single species stand and a seed mixture.

Figure I1. Three different seed types: Left-wheatgrass seed (western wheatgrass: 7-15 lbs PLS/acre); Right-fluffy seed (sideoats grama: 4-8 lbs PLS/acre); Bottom-small seed (inland saltgrass: 5-10 lbs PLS/acre). Seeding rates depend on the size of seed.

Calculating Seeding Rates

Information needed to calculate PLS pounds/acre for seeding a single species:

- Number of seeds per square foot (25 seeds/ft^2)
- Number of seeds per acre, based off seeds per square foot
- Known number of seeds per pound for the species (western wheatgrass = 115,000 seeds per pound(Taliga 2011))
- If calculating the rate for a seed mixture, use the percentage for each grass in the mixture

Calculating Seeding Rate for a Single Species

$$\frac{\#\ of\ seeds}{ft^2} \times \frac{43{,}560 ft^2}{1\ Acre} \times \frac{l\ lb}{\#\ of\ known\ seeds} = \frac{lbs\ of\ seed}{1\ Acre}$$

1. $\frac{25\ seeds}{ft^2} \times \frac{43{,}560 ft^2}{1\ Acre} = \frac{1{,}089{,}000\ seeds}{1\ Acre}$
2. $\frac{1{,}089{,}000\ seeds}{1\ Acre} \times \frac{1\ lb}{115{,}000\ seeds} = \frac{9.47\ lbs}{1\ Acre}$

   9.47 PLS lbs/acre is the seeding rate for a solid stand of Western wheatgrass

Calculating Seeding Rate for Mixed Species

3. To calculate the rate for western wheatgrass in a seed mix, multiply the solid stand rate (9.47 lbs/acre) by the percentage of the species in the mixture (i.e. 15% of the total seed mix is western wheatgrass)

$$\frac{9.47\ lbs}{1\ Acre} \times 15\% = \frac{1.42\ lbs}{1\ Acre}$$

Steps 1-3 should be repeated for all other species in the seed mix to determine the total pounds of seed mix per acre.

Appendix J. Controlling kochia and downy brome in revegetation projects

The following section provides necessary steps needed to perform timely adaptive management in revegetation projects. These recommendations should be used for all seeding projects and can be adapted according to project goals.

1. Initial weed control must be provided in the spring and summer before grasses are seeded in the fall of the same year. Apply glyphosate or broadleaf selective herbicides and continue monitoring throughout the growing season to make sure all weeds are controlled. Multiple applications of glyphosate may be needed to control weeds over the season.
2. After seeding, monitoring should start in the late winter/early spring to evaluate weed invasion, erosion issues, wildlife presence, etc. Weed control will be the most important factor to monitor after seeding. Monitoring over the course of the growing season is imperative for proactive weed management. Monitoring should be done for the next two years to evaluate grass establishment and weed invasion.
3. Kochia and downy brome are likely to germinate before seeded grasses in early spring the first year after seeding. This is an ideal time to control these weeds without injuring seeded grasses. Downy brome can germinate in the fall and overwinter; therefore, a late-winter, or early-spring, glyphosate application should be made.
    a. Glyphosate – 16 oz/acre
    b. Apply glyphosate to kill germinated weeds. This will not kill grasses. <u>Only apply if seeded grasses have not emerged.</u>
    c. New kochia and downy brome will germinate after this initial application due to favorable conditions, such as moisture and cooler temperatures. Glyphosate may need to be reapplied. O<u>nly apply if seeded grasses have not emerged.</u>

4. If kochia and downy brome are present after the grasses have emerged, use selective herbicides. Vista® (fluroxypyr) is a great option to control kochia. Options for selective downy brome control are limited in a grass system; therefore, only kochia (and other broadleaf weeds) can be controlled at this point.
    a. Vista – 12 oz/acre for kochia <8 inches tall; higher rates may be necessary for larger kochia plants
    b. Dicamba – 4-16 oz/acre provides control for actively growing and/or established kochia; recommended to use in combination with Vista if kochia is >8 inches and after seeded grasses are past the 3-leaf stage
    c. 2,4-D – 1 pint/acre provides control for actively growing broadleaf weeds that cannot be controlled using Vista. Apply when weeds are <8 inches tall. 2,4-D will not kill kochia but will control several other broadleaf weeds.
5. Because the Vista label allows only 23 oz/acre to be applied per year, this limits the number of applications that can be made. In the late spring, if the kochia does get too large and Vista has already been applied at 12 oz/acre, the Vista rate cannot be increased to control larger plants. Adding dicamba at 1 pint/acre in a tank mix with Vista will increase control without injuring grass seedlings.

   In a more ideal situation, if kochia is monitored and sprayed before it reaches 8 inches, two applications of Vista can be made at 12 oz/acre and 11 ounces/acre. This should provide excellent control.
6. Mowing is another option when kochia is too big to control with the recommended Vista rate. Mow the kochia to <4 inches tall and apply Vista at 11-12 oz/acre. This allows for better coverage and plants are less likely to recover if they have been

mowed. This significantly reduces the kochia competition as the seeded grass are trying to establish.

7. When making these applications to growing plants, using an effective surfactant is very important. The Vista herbicide label recommends MSO as a surfactant. This results in better herbicide absorption into the plant compared to NIS.
8. For seeding projects, residual and selective herbicides can be applied at the end of the growing season, if grasses are at the 2-3 leaf stage with at least one tiller. Esplanade (7 oz) + Method (8 oz) is recommended for providing residual downy brome and kochia control, in addition to several other broadleaf weeds. Expect at least two years of weed control with this treatment. Apply in late August or September.

Quick Reference Re-seeding Tips (Sebastian 2018)

Winter annual weeds: downy brome, Japanese brome, feral rye, prickly lettuce, flixweed

- Newly seeded sites are prone to failure if winter annual weeds are not controlled
- Spray in the spring after winter annuals have emerged and before seeded grasses emerge
- Treat with glyphosate in late winter or early spring before seeded grasses emerge in the first year
- Glyphosate will not injure the grasses if they have not emerged or if they are still dormant in the second year
- If kochia has emerged in the early-spring, Vista should be added to the tank mix
- Follow herbicide label rates and application recommendations

Spring annual weeds: kochia, prickly lettuce, flixweed

- Newly seeded sites are prone to failure if spring/summer annual weeds are not controlled
- Vista, 2-4,D and dicamba are effective herbicides for controlling broadleaf weeds in

seedling grass.

- Broadleaf weeds (i.e. kochia) are much easier to control when they are seedlings, <3 inches tall
- Esplanade is excellent for controlling winter and spring annuals in established grass systems. Apply after grasses are established. Method is excellent for controlling field bindweed and several broadleaf annuals and is a great preemergence kochia herbicide.
- Always follow herbicide label rates and application recommendations.

Appendix K. Cost Comparisons for Restoration Projects

Costs for Landside Revegetation Projects

Table K1. Costs associated with each input for separate revegetation projects from 2014-2017. This illustrates which inputs are the most expensive.

Cost Description	**2014 WO-015 Project**	**2014 WO-012 Project**	**2014 WO-06 Project**	**2016 Roadway Erosion Control #1**	**2016 Roadway Erosion Control #2**	**2017 Roadway Erosion Control**	**Pena South Parcel Fill**
Area (acres)	**1.7**	**1.6**	**2.5**	**1.5**	**1.7**	**6.2**	**8.2**
Total Cost	**$24,921**	**$22,385**	**$44,292**	**$62,910**	**$87,791**	**$209,921**	**$40,431**
Topsoil (cubic yards)	**$22,564** @ $24.5/CY	**$21,168** @ $24.5/CY	**$40,827** @ $31/CY	**$55,624** @ $68/CY	**$63,403** @ $71/CY	**$144,552** @ $24/CY	**$25,552** @ $8/CY
Seeding (acres)	**$725** @ $426.5/ac	**$682** @ 426.5/ac	**$1,066** @ $426.5/ac	**$1,873** @ $1,249/ac	**$2,123** @ $1,249/ac	**$6,665** @ $1,075/ac	**$4,100** @ $500/ac
Mulching (acres)	—	—	—	**$1,593** @ $1,062/ac	**$1,805.40** @ $1,062/ac	**$3,500** @ 1,400/ac	**$2,765** @ $350/ac
Hydro Mulching (acres)	**$1,631** @ $959.5/ac	**$1,535** @ $959.5/ac	**$2,398** @ $959.5/ac	—	—	—	—
Mulch Tackifier (pounds)	—	—	—	**$2,250** @ $5/lb	**$1,750** @ $5/lb	**$9,100** @ $3.50/lb	**$3,476** @ $2.2/lb
Soil retention blanket (square yards)	—	—	—	**$2,070** @ $7.5/SY	**$18,210** @ $7.5/SY	**$46,104** @ $3/SY	**$4,538.** @ 3.10/SY

- Past landside revegetation projects at DEN have required multiple inputs to revegetate a very limited number of acres. These projects range from $22,000-$210,000 depending on the project size and site conditions. Each of these projects were less than 10 acres in size.
- They are expensive and delivered mixed results.
- Each project listed in Table K1 has resulted in little to no grass establishment, while being heavily impacted by downy brome and kochia.
- The amount of money spent on these projects should have provided a successful outcome.

- Currently, effective weed management is not provided for any revegetation projects. Without effective weed control, revegetation projects will fail.
- We recommend including weed control over a three-year time frame to ensure grass establishment before closing project contracts.
- Importing topsoil is not always required for revegetation and is one of the most expensive inputs for these projects (Table K1). Adding topsoil to these sites makes up 60-90% of costs for these projects. Standard soil tests should be conducted to determine soil texture, organic matter, macro and micronutrients, and soil salinity caused by magnesium chloride before considering importing topsoil. Soil from a project site may be in a better condition compared to imported topsoil. Topsoil from an outside source is not always higher in organic matter and nutrients, having little to no added benefits compared to the soil removed from the site.
- Anytime a major project is considered, "native" soil should be removed, stockpiled, and returned to the site before seeding. This could reduce input costs into these projects. Costs associated with purchasing topsoil, transporting, and spreading it are significantly reduced when "native" topsoil is used.
- Soil bed preparation is not always necessary. Tillage can disturb the soil and promote weed germination, causing a larger weed problem. In addition, it can lead to soil moisture loss that is essential for grass establishment.
- DEN should consider purchasing their own rangeland drill and grass seed to complete seeding projects at DEN. Having this capacity in house can greatly reduce the seeding costs (Table K2) and allow for more control over the project. Seed costs will vary

depending on the species. Purchasing bulk seed can greatly reduce total revegetation costs. Several seed mixes have been provided to DEN in appendix H.

- Broadcast seeding, hydroseeding and erosion control techniques will depend on the project site. At DEN, seeding is often done through broadcast seeding or hydroseeding, which both have had very low success rates.
- Drill seeding can be a more cost-effective method and should be used in sites that are accessible. The seeding rate is almost doubled for broadcast and even higher for hydroseeding. Grass establishment with drill seeding has resulted in greater success, and it can also be a cost savings due to lower seeding rates.
- Soil retention blankets and mulch tackifiers are not always a necessary input. For sites on level ground or with little or no slope, retention blankets are not always required.
- Using hydro mulching or soil retention blankets will depend on the project and should be determined by the project manager.
- For the purpose of this cost comparison, we are not recommending either for seeding projects. It will be dependent on the project site conditions; however, several areas that are candidates for seeding would not require erosion control blankets. Mulching and a mulch tackifier may be more beneficial for those sites to minimize wind erosion.

The table below provides a cost breakdown for the recommended three-year revegetation process (Table K2). These annual costs are estimates, as they will likely change depending on the project and site conditions. The goal for this analysis is to show DEN the potential cost savings by completing revegetation projects in-house that are associated with not using topsoil, purchasing recommended seed mixes, investing in a rangeland drill, and providing weed control.

The cost per acre for the rangeland drill is based on the Truax Company suggested retail price (MSRP) and the total number of acres that were revegetated in 2014-2017 (23.4 acres). This is a theoretical price as the number of acres revegetated annually and the price of the drill will vary, but it gives DEN an idea of what the return on investment could be for a new rangeland drill over a short time period. Current seeding costs, on average, are $764 per acre. This cost includes the price of seed, equipment, and labor.

Based off the MSRP of a drill (i.e. $30,000), the number of acres revegetated, the cost of seed, and labor, DEN could do their own seeding for $1,358 per acre (Table K2) in the first year of the three-year process. Although this cost is more than the current average seeding costs, it would significantly decrease once the cost savings offset the cost of the drill, with seed and labor being the only costs for future projects. DEN could save ~$900 ($100 for seed) on seeding if done in-house versus a contractor (Table K3). Between the costs savings from seeding in-house and the price of the rangeland drill, it would take DEN ~33 acres to pay off the drill. This quick return on investment is another way to show the value of investing in a drill to complete seeding projects in-house. In addition, the cost savings from not hiring contractors for every project would be significant over the long-term (Table K3). For this cost analysis, labor costs from the 2018 mowing expenses ($156,484) and labor hours (3,379 hours) were used(Brannan 2019).

Table K2. CSU recommended revegetation inputs and costs over a three-year period. Costs after the first year will decrease and weed control and monitoring are the two major costs for the next two years.

Revegetation Task	**Cost per acre**	**Time of Year**		
Year 1		**Spring**	**Summer**	**Fall**
Weed Control – Glyphosate @ 2pts/ac – 3 times	$17.25	1X	2X	
Labor/herbicide application cost @ $41.80/hr*, spray 16 acres/hr	$2.60	X	X	
Grass seed (new seed mix Figure I1) Or crested wheatgrass – monoculture stand @ $4.15/lb, planting rate @ 7 lbs/ac	$46 $29			X
Truax Rangeland Drill (purchase new @ $30,000/23.4 revegetated acres in 2014-2017)	$1,282			X
Labor/seeding costs @ $41.80/hr, plant 4 acres/hr	$10.70			X
Total cost per acre – Year 1	***$1,358.55*** ***$1,348****			
Year 2		**Spring**	**Summer**	**Fall**
Weed control – Glyphosate @ 2 pts/ac – 1 time 2,4-D @ 1pt/ac + Vista @ 12 oz/ac – 2 times	$51.40	Glyphosate Dormant season-1X	2,4-D + Vista 2X	
Labor – application costs	$2.60	X	X	
Monitoring @ $41.80/hr, ~1 workday to evaluate project sites (10 hours), 1 time/yr	$418	1X	1X	
Total cost per acre – Year 2	***$472***			
Year 3		**Spring**	**Summer**	**Fall**
Weed control – 2,4-D @ 1pt/ac + Vista @ 12 oz/ac – 2 times Esplanade @ 7 oz/ac + Method @ 8 oz/ac – 1 time	$136.60	2,4-D + Vista 1X	2,4-D + Vista 1X	Esplanade + Method 1X
Labor – application costs	$2.60	X	X	X
Monitoring	$418	1X	1X	
Total cost per acre – Year 3	***$557.19***			
Total cost for 3-year process	***$2,100.20*** ***$2,071.20****	*Costs including crested wheatgrass in place of a grass seed mix.		

Table K3. Cost comparisons by year for revegetation efforts completed by DEN versus a hired contractor.

Revegetation Task Completed In-House or Contracted	**Cost per acre**
Year 1	
DEN (In-house)*	$1,358.55
Contractor** – Weed Control and Seeding	$2,000
Year 2	
DEN (In-house)	$472
Contractor – Weed Control	$1,000
Year 3	
DEN (In-house)	$557
Contractor – Weed Control	$1,000
Total costs for 3-year process	
DEN (In-house)	**$2,100.20**
Contractor	**$4,000.00**

*The price breakdown for DEN yearly costs can be found in Table K2.
**Prices for revegetation work were provided by a local reclamation company located in Keenesburg, CO. Weed control includes labor, chemical, and equipment costs. No follow-up monitoring is provided in this cost. Seeding costs include soil-bed preparation (i.e. tillage, disking, and drill-seeding).

Table K3 illustrates the cost savings associated with completing revegetation projects in-house, compared to a hired contractor. Prices are provided by only one company and may not represent all possible contracting work available in Colorado; however, this estimate shows that DEN would pay about half of what it would cost to hire a contractor to complete similar tasks across the recommended 3-year process (Table K3). DEN would be able to provide annual weed control and monitoring for half the cost of a contractor, which only provides weed control and no adaptive management without additional costs. Seed costs are greatly reduced compared to a contractor. It is not always necessary to perform soil-seed bed preparation; therefore, those prices are not included in the seeding price for DEN.

Weed control is essential for successful grass establishment; therefore, we recommend following a three-year process. Sites need to be monitored and adaptively managed each year. For best management practices, follow the recommendations provided in Appendix J. It is important to note that even with effective and timely weed management, revegetation projects can fail. Although weed control plays an important role in establishing grasses, environmental conditions, such as timely precipitation, are just as, if not more important. In years with below average rainfall, it will be extremely difficult for grasses to establish and persist. Be prepared for these failures to occur and understand that revegetation is an unpredictable and long-term process.

Appendix L: Bare Ground Weed Management

The following information provides recommendations for providing total vegetation control/bare ground on DEN property. Bare ground treatments are used to control all vegetation present, including invasive and desirable species; therefore, it is important to apply the recommended herbicide treatments according to the label and in areas that do not have desirable vegetation present. Bare ground weed control relies heavily on soil residual herbicides that will provide at least one full year/season of control.

Providing bare ground in a variety of different rights-of-way, fence lines, parking lots, etc. is necessary to prevent wildlife hazards, increase visibility, and reduce wildfire hazards. Apply these treatments along roadsides, airfield runways, fence lines, light rails, railroads, and oil well and gas pads.

Table L1 provides a list of herbicide combinations that will control a wide spectrum of weeds. The most common weeds in the areas listed above include downy brome, kochia, field bindweed, and a few other summer annual weeds; therefore, some of these treatments are designed to target those species while others will control all vegetation present.

Table L1. Bare ground herbicide treatments for DEN property.

Herbicide Treatment (oz/ac)	Cost ($)/acre	Weeds Controlled	Application Timing	Comments
Plainview SC (32 – 64 oz)	$62-124.16	All vegetation	Fall or Spring	Provides pre-emergence and postemergence control. Top recommended treatment.
Method (10 oz) + Esplanade (7 oz)	$88.75	downy brome, kochia, field bindweed, prickly lettuce, thistle species	Fall or Spring	Pre-emergence and postemergence control. Add Telar (1.5) oz to control curly dock if present.
Piper (10 oz) + Method (5 oz) + Esplanade (7 oz)	$120.01	Same weeds as above.	Fall or Spring	Pre-emergence and postemergence control. Piper provides control for actively growing kochia in addition to residual control.
Piper (10 oz) + Esplanade (7 oz)	$107.61	downy brome and kochia	Fall or Spring	Pre-emergence and postemergence control. Selective bare ground treatment – use in areas with trees or shrubs.

Considerations and comments:

1. Bare ground treatments can be made in the fall or spring; however, CSU and industry research has shown a fall-timing application is most effective in providing year-long control (Sebastian et al. 2020).
2. Include glyphosate to herbicide treatments to control any growing vegetation. Several of these products are soil-residual herbicides that need to be activated by moisture before they are effective; therefore, they will not provide immediate control for all weeds once applied.
3. Plainvew SC is composed of Esplanade, Method, and Imazapyr. This treatment has been very successful in providing up to 2 years of control at multiple research sites across

Colorado, including a site established on Pena Boulevard and E 40th Avenue (Figure L1). This top performing treatment will provide effective control for a wide variety of weeds and is recommended as the main bare ground treatment for DEN.

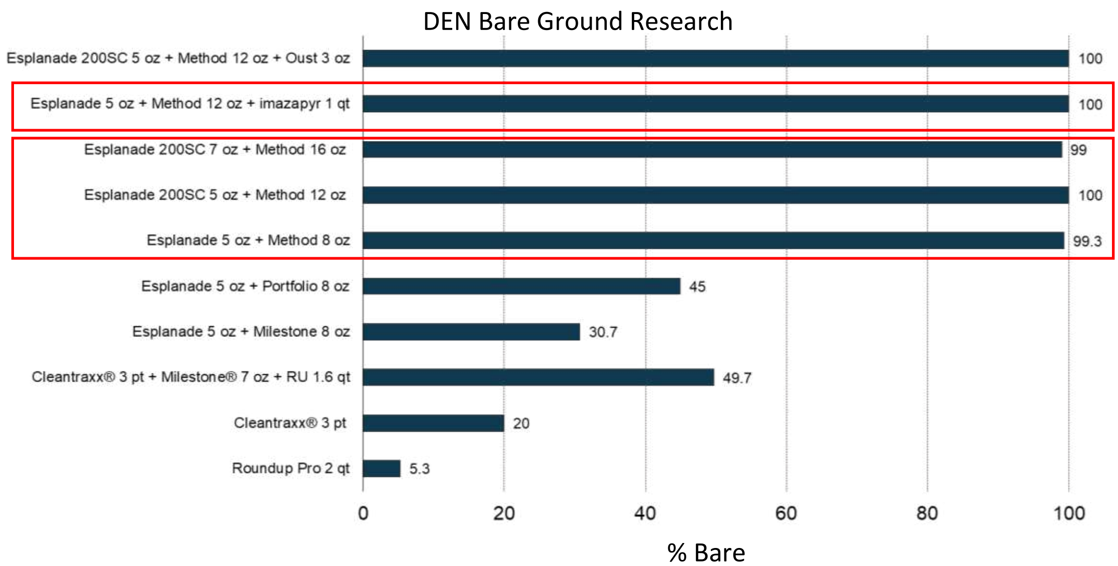


Figure L1. Bare ground research evaluations made 6 months after treatment. Bars and numbers represent % bare ground observed at the time of evaluations. Weeds present at the site were kochia, downy brome, Russian thistle, and field bindweed.