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Transplanting Mature Mountain Big Sagebrush Plants Yields High First-Year Survival in Dryland Pasture Restoration

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TRANSPLANTING MATURE MOUNTAIN BIG SAGEBRUSH PLANTS YIELDS HIGH FIRST-YEAR SURVIVAL IN DRYLAND PASTURE RESTORATION

by

Elizabeth C. Bailey

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

of

MASTER OF SCIENCE

in

Ecology

Approved:

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UTAH STATE UNIVERSITY
Logan, Utah

2021

ABSTRACT

Transplanting Mature Mountain Big Sagebrush Plants Yields High First-year Survival in Dryland Pasture Restoration

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Utah State University, 2021

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Human activities such as agriculture, livestock grazing, mining and urban development have contributed to the degradation and loss of rangelands worldwide. A need for reestablishing sagebrush rangelands in disturbed landscapes across the Western United States, including former dryland pastures, has been identified but traditional, primarily seeding-based, restoration methods have largely been unsuccessful. To improve restoration outcomes, there has been increased interest in the planting of containerized greenhouse “tubelings”, but transplanting of mature plants, “wildlings”, remains relatively unexplored. Survival of tubelings vs. wildlings and under what conditions these techniques might be suitable are unclear. Here we tested establishment of mountain big sagebrush (*A. tridentata ssp. vaseyana*) from planting tubelings vs. wildlings. Research was conducted in southeastern Idaho where vegetation was dominated by two introduced grasses, Smooth brome (*Bromus inermis*) and Kentucky bluegrass (*Poa pratensis*). Following extensive seedbed preparation and application of herbicide, the study area was drill-seeded with a mix of rangeland species. We then established thirty-six 80 m x 80 m plots, each of which received one of three sagebrush establishment methods: tubelings vs. wildlings, plus seeding for comparison over the long term. Another six plots were established as controls (no sagebrush). In each of the assigned treatment plots, crews planted 100 tubelings/wildlings (n=1200 tubelings; 1200 wildlings) and broadcast seeded at a rate of 0.5 lbs pls per acre in October and November 2019. In addition to assessing planting quality and frost heaving at the time of planting, we recorded plant survival the summer and fall after planting, as well as other measurements such as vigor, plant height, physical damage, and reproduction. Survival of wildlings one year after planting was significantly higher than that of tubelings (92% and 17% respectively). Poor planting quality (e.g., exposed roots or air pockets in the soil) was significantly associated with tubeling mortality, indicating that quality of planting performed by vegetation crews needs to be more closely examined. The results of this study illustrate that wildlings can yield very high one-year survival rates (especially compared to tubelings) and suggest that, when conditions are appropriate, wildlings may be a more cost-effective method for establishing sagebrush.

(69 pages)

PUBLIC ABSTRACT

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Approximately 10-20% of global dryland ecosystems are severely degraded, an amount that is expected to increase, threatening the environment and ecosystem services that 38% of the global population relies upon. Human activities such as agriculture, livestock grazing, mining and urban development have contributed to the degradation and loss of rangelands worldwide. A need for reestablishing sagebrush in disturbed landscapes across the Western United States, including dryland pastures, has been identified but traditional, primarily seeding-based, restoration methods have largely been unsuccessful. To improve restoration outcomes, there has been increased interest in the planting of containerized greenhouse "tubelings", but transplanting of mature plants, "wildlings", remains relatively unexplored. Survival of tubelings vs. wildlings and under what conditions these techniques might be suitable are unclear. Here we tested establishment of mountain big sagebrush (*A. tridentata ssp. vaseyana*) from planting tubelings vs. wildlings. Research was conducted in southeastern Idaho where vegetation was dominated by two non-native grasses which are a concern for land managers. Following seedbed preparation and application of herbicide, the study area was drill-seeded with a mix of rangeland grasses and forbs. We then established thirty-six research plots, each of which received one of three sagebrush establishment methods: tubelings vs. wildlings, plus seeding for comparison over the long term. Another six plots were established as controls (no sagebrush). In addition to assessing planting quality and frost heaving at the time of planting, we recorded plant survival the summer and fall after planting, as well as other measures such as percent green leaves present, plant height, physical damage, and reproduction. Survival of wildlings one year after planting was significantly higher than that of tubelings (92% and 17% respectively). Tubeling mortality had a significant association with the poor planting variable (e.g., exposed roots or air pockets in the soil), indicating that quality of planting performed by vegetation crews needs to be more closely examined. The results of this study illustrate that wildlings can yield very high one-year survival rates (especially compared to tubelings) and suggest that, when conditions are appropriate, wildlings may be a more cost-effective method for establishing sagebrush.

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Elizabeth C. Bailey

CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The extent of intact drylands has been reduced by human activities such as agriculture, livestock grazing, mining and urban development, and the condition of drylands is further threatened by invasion of non-native species, encroachment of woody species, and the effects of climate change including increased aridity and temperature and more severe fire regimes (Hoover et al. 2020; Maestre et al. 2016; Knick et al. 2003). Approximately 10-20% of global dryland ecosystems are currently severely degraded, an amount that is expected to increase, threatening the environment and ecosystem services upon which 38% of the global population rely (Yirdaw et al. 2017; Lu et al. 2018; Hoover et al. 2020; Maestre et al. 2016; Bestelmeyer et al. 2015). There is a global need for restoration of drylands, as well as for research into new and innovative dryland restoration practices as traditional methods often fail to re-establish desired species (Copeland et al. 2021).

Restoration is a major priority in sagebrush ecosystems of the western U.S., which once covered 63 million hectares but have been reduced to half of their historic extent (Knick et al. 2003; Pyke 2011). In these landscapes, broadscale land management projects often are aimed at re-establishing sagebrush communities in wildlands following fire (Arkle et al. 2014; Pilliod et al. 2017). These extensive restoration efforts typically rely on traditional approaches, primarily seeding, a method which has been found to be unreliable for establishing plant cover and contingent upon sufficient soil moisture (Banerjee et al. 2006; Shriver et al. 2018; Havrilla et al. 2020) and most likely to yield successful establishment at higher elevations sites with higher annual precipitation (Shriver et al. 2018; Svejcar et al. 2017). Overall, attempts to establish the foundational woody species, sagebrush (*Artemisia tridentata*), from seed have been costly and largely unsuccessful (Pilliod et al. 2017; Knutson et al. 2014; Boyd & Davies 2012).

Successful establishment of sagebrush from seed faces an array of challenges, many of which could potentially be ameliorated by outplanting more mature plants instead of direct seeding: short seed longevity, limited soil moisture, high interannual weather variability, and resource competition with both native and introduced species (Meyer 1992; Lambert 2005). In sagebrush ecosystems, establishment from seed is limited by an establishment bottleneck which occurs within the first year during germination and seedling emergence. The benefits of bypassing this bottleneck have driven a growing interest in planting containerized greenhouse seedlings ("tubelings") of sagebrush (Germino et al. 2018). In a literature review of 120 experiments using seeds and seedlings in a variety of ecosystems, Palma & Laurance (2015) found that survival was higher for planting seedlings than direct seeding. Although they have higher associated costs (i.e., soil, containers, seed, greenhouse space, water, personnel expenses for watering, transportation and planting), sagebrush tubelings of big sagebrush (*Artemisia tridentata*), have been shown to yield high survival rates (e.g., 58% 2-year survival, Davidson et al. 2019),

A less explored alternative to use of tubelings in restoration projects is the transplantation of mature sagebrush plants ("wildlings") from nearby intact stands. A handful of wildling studies of sagebrush investigated transplanting plants as "bare root" stock, an approach which can leave plants vulnerable to transplant shock and damage during transplantation, and lead to more variable survival rates overall (Grossnickle & El-Kassaby 2016; Mckay 1996; Grossnickle 2012). A more promising, almost entirely unexplored, approach entails transplanting wildlings with an intact soil root ball. Though considered more costly due to personnel expenses for harvesting and planting, sagebrush wildlings in a handful of studies exhibited high survival rates (McArthur & Plummer 1978; Shumar & Anderson 1987; Luke & Monsen 1984), which highlights the need for further investigation of wildlings as an approach to re-establishing sagebrush in disturbed lands. Although plantings of tubelings and wildlings have each yielded high rates of sagebrush establishment in restoration studies (McArthur 2004; McAdoo et al. 2013; McArthur & Welch 1982; Davidson et al. 2019), we found only one direct comparison for *ssp. wyomingensis*, and no direct comparisons for *ssp. vaseyana*, a subspecies that occurs in wetter sites and establishes at higher densities. Both tubelings and wildlings have generally been considered cost-prohibitive for land managers due to their upfront cost but considering the cost per established plant, i.e, "cost as modified by the probability of success" (sensu Boyd & Davies 2012) is necessary for evaluating the efficacy of the different methods.

While restoration of sagebrush ecosystems stands to benefit from improvement of how plants are being restored (e.g., use of wildlings), significant improvement could also be made by considering which type of sites are targeted for restoration. There are approximately 237 million hectares of grassland pasture and range in the United States (Lubowski et al. 2006). Many of these grassland pastures are dominated by introduced forage grasses, such as smooth brome and Kentucky bluegrass, which have invaded grasslands and disturbed areas across North America (Otfinowski et al. 2007; DeKeyser et al. 2015). With abandonment of these types of agricultural lands growing globally, broadening restoration efforts to include dryland pastures would expand the total extent of potential sagebrush lands (Cramer et al. 2008; Uselman et al. 2018). Moreover, dryland pastures also provide unique opportunities to improve the restoration process, such as greater accessibility by machinery and crews, or availability of irrigation systems.

Uselman et al. (2018) found that restoration of agricultural drylands is possible but outcomes vary drastically depending on ecological context. Aside from dryland pastures typically being dominated by grasses that were intentionally chosen for their competitive ability and resiliency, additional restoration challenges that may be exacerbated in dryland pastures include: paucity of native species in the seedbank, low nutrient availability, lack of soil crusts, and issues with soil degradation or compaction (Bainbridge 2012; Benayas et al. 2008; Uselman et al. 2018). Current practices of rehabilitating agricultural lands typically include seeding following suppression of undesirable plants with herbicide, mechanical reduction or burning, but these methods often are not sufficient for establishment of desirable native plants (Bahm et al. 2011; Krueger-Mangold et al. 2006; Svejcar et al. 2017; Grygiel et al. 2009). Similar to wildland settings, planting containerized sagebrush plants in order to increase establishment success could improve restoration outcomes.

The objective of this study was to directly compare short-term survival of tubelings and wildlings of mountain big sagebrush (*A. tridentata vaseyana)* in the context of rehabilitation of former dryland pastures, as well as compare costs between the two methods. We also established broadcast seeding plots as basis for future comparisons since seeding is the method most commonly used by managers for landscape-scale restoration projects in the region.

METHODS

Study area

This research was conducted on the nearly 1605-hectare Fox Hills Ranch (owned by Bayer since 2008) approximately 10 miles northeast of Soda Springs, ID in Caribou County (42.769415, -111.472490) (Fig. 1). In the past forty years, a weather station 20 km away from the project site (Station ID USS0011G01S; Somsen Ranch) had a mean annual precipitation of 641 mm (range: 94 mm - 888 mm). The majority of precipitation falls as snow from November to January and there is a pronounced dry period from June to September. The year of implementation, 2019, was slightly wetter than average with a total of 720 mm (53 mm in October and 28 mm in November when seeding and planting occurred). The first year following planting, 2020, was slightly drier than usual (628 mm total) but had significant precipitation events throughout the winter and in June (91 mm compared to a historic average of 40 mm). A large portion of Fox Hills Ranch was previously converted by prior owners from sagebrush steppe habitat to introduced grasses to enhance livestock forage (see below). The entire 1605 hectares of Fox Hills Ranch supports an average of 2600 AUMs of cattle annually and is grazed early summer through mid to late October. The soils at this site are loamy and well-drained (Salsbury et al. 2019).

The project area is 96 hectares (238 acres) of the ranch that was fenced into two grazing pastures. Livestock grazing ceased within the project area after applying a heavy grazing treatment for our study in September and October 2018. The project area was dominated by the introduced perennial grasses smooth brome (*Bromus inermis*) and Kentucky bluegrass (*Poa pratensis*). Smooth brome and Kentucky bluegrass are sodforming grasses that have been widely introduced across the United States for cattle forage, and their dominance and suppression of native species establishment and succession are now of concern to land managers (Bahm et al. 2011). There were scattered mountain big sagebrush (*A. tridentata ssp. vaseyana*) throughout the project area with increased densities along the southern and western boundaries. Elevation varies from 1926 m to 1966 m.

In October of 2018 the entire project area was disced (three passes; Case IH Ecolo Tiger 870 22' Disc Ripper) and received a final pass with a harrow (60' 15 Bar McFarlane Harrow Cart). An herbicide mixture of glyphosate (Roundup Power Max, Monsanto Company, St. Louis, MO) and dicamba (Vision, Helena Agri-Enterprises, LLC) was applied with a boom sprayer (Case SPX 4430) at rate of 2.33 liters / hectare and 0.15 liters / hectare respectively, on July 31st, 2019 to reduce cover of the introduced grass forage grasses. On the 24th and 25th of September, 2019, final seedbed preparation was completed in the project area with one pass of a chisel plow and one pass with a harrow.

In October 2019, the project area was drill-seeded with a seed mix (purchased from ACF West, Boise, ID) comprised of twenty-two rangeland species that included eight perennial grasses and fourteen perennial forbs, the majority of which were selected to provide cover and support the dietary needs of the Greater Sage-Grouse (*Centrocercus urophasianus*) (Table 1). Of the 238 acres in the project area, 213 acres were seeded at a rate of 12.85 lbs pls / acre with a precision drill seeder (Truax OTG, New Hope, MN) with 18 opener discs (19.05 cm apart) at a depth between .95 cm and 1.27 cm. Due to several early season storms, 21 of the remaining acres were inaccessible by the drill seeder and were instead broadcast seeded using a Brillion seeder at double the original seeding rate (25 lbs pls / acre) to compensate for reduced efficacy of broadcast vs. drill-seeding. Six acres were on a steep slope and inaccessible due to wet conditions.

Experimental design

This study employed a randomized design with thirty-six 80 m x 80 m plots receiving one of three sagebrush establishment methods in October/November 2019 (tubelings vs. wildlings vs. seeding, the latter established as a basis for comparison over the long term), and another six 80 m x 80 m plots designated as controls (no sagebrush) (Fig. 1). An additional six plots outside of the project area in untreated grazing pasture served as reference sites. There was a buffer of at least 15 m between all plots. For all three sagebrush establishment treatments, sagebrush was installed in four 15 m x 15 m sagebrush “islands" per plot (Fig. 2); islands were located 10 m apart (high density) in half the plots and 30 m apart (low density) in the other half, as part of a larger, long-term study investigating the effects of island density. For tubeling and wildling treatments, each island contained twenty-five mountain big sagebrush individuals planted in a 5 m x 5 m grid, with plants spaced by 3 m (Fig. 2). Seeded islands were broadcast seeded by hand with mountain big sagebrush seed at a rate of 0.5 lbs of pure live seed per acre, which is the highest density that is recommended to establish a sagebrush stand (Meyer 2008; Jacobs et al. 2011).

Plant materials and planting technique

Tubelings were grown by North Fork Native Plants (Rexburg, ID). Sagebrush seed was sown into 10 in^3 containers (Ray Leach Cone-tainers) from 7/1/2019 to 7/11/2019. Containers were reseeded if no seedlings emerged. Tubelings were 4 to 5 months old at the time of planting. Plants were delivered on October 14th and remained outside on site until the end of planting. Dibbles, or dibble-sticks, were used to create each hole, and tubelings were placed in holes by crew members who were instructed to subsequently firm the surrounding soil. No supplemental water was applied to transplants. Seed was purchased from Utah Seed in Tremonton, UT. Seed had been collected in fall of 2018 from sagebrush stands near Logan, Utah, approximately 85 miles from the project area, in a similar elevation and climate regime (41.557240, -111.808770).

Wildling plants were harvested by vegetation field crew members from the nearby Caldwell Canyon, approximately 7 miles from Fox Hills Ranch (42.722228, -111.35985). Crew members used shovels to dig up target plants and a shovel-blade-sized amount of dirt surrounding the root ball. The plants were wrapped in burlap and secured with twine, transported to the field site, and planted the same day as collected. The age of wildlings was unknown at time of planting; however, plants were small (6 – 25 cm tall) and non-reproductive. A shovel was used to create holes, and the wildlings were removed from the burlap and placed inside the hole, and soil was compressed around each plant. Planting was completed from October 15th to November 11th, 2019. No supplemental water was applied to transplants.

For the seeded treatment plots, islands were divided into five rows (3 m wide) and crew members were given a cup of seed filled with the amount to yield a seeding rate of 0.5 lbs pls per acre (Hoag et al. 2002). Crew members then hand-scattered the seed evenly across each row and used a push roller (approximately 46 cm x 61 cm) across the island to increase seed to soil contact by pressing seed into the soil. We used the same seed as we did for growing tubelings, and seeding occurred October 24th through November 11th, 2019. We complemented this portion of the experiment with small plot field trials to test effects of season of seeding and local seed sourcing (Appendix A).

Data collection

Within five weeks of our October/November 2019 planting the following measurements were taken on all tubelings (n = 1200): vigor (a visual estimate of percentage of green leaves, 0-100%, by increments of 5), height (nearest cm), crown size (longest axis and perpendicular axis in cm), physical damage (presence / absence), frost heaving (presence / absence) and planting quality (presence / absence of exposed roots or air pockets). If more than one tubeling was growing within one container, "more than one" was noted during the first assessment and the additional plants were randomly selected to be clipped. Assessments including survival status, vigor, and reproduction (presence / absence), were repeated in the summer (June 2020) and fall (October 2020) following planting for all tubelings.

Due to a limited sampling window before the site would become inaccessible due to weather, only a subset of wildlings (n = 297) were assessed within five weeks of planting in Oct/Nov 2019 for vigor, height, crown size, physical damage, and planting quality. In June 2020, these same variables (except planting quality), plus reproductive status (presence / absence), were recorded for all wildling plants. One-year post-planting, in October 2020, wildling survival status, vigor, and reproduction were assessed.

For both tubelings and wildlings, any observed rodent damage (severed stems, holes around base of plant, etc.) or insect damage (galls, aphids, etc.) was recorded for each plant during every assessment.

For the seeded sagebrush treatment plots, in July and August of 2020 (i.e., late summer after seeds were sown), we assessed density of sagebrush seedlings in two 0.25 m^2 frequency frames placed within each of the four islands in each 80 m x 80 m seeded plot. We repeated assessments in October of 2020, but with four 0.25 m^2 frames placed randomly in each island.

To monitor plant community composition in the first growing season post-implementation (July and August of 2020), ten 0.25 m^2 frequency frames were placed within each of the 42 experimental plots (420 frames total). In the seeded and control plots, placement of eight of these frequency frames occurred by generating two random points within each of the four islands (eight points per plot). In tubeling and wildling sagebrush treatment plots, in each of the four islands, one frame was placed in the canopy of a randomly selected sagebrush, and another was placed in the interspace between two randomly selected sagebrush plants (eight points per plot). In all four plot types, the remaining two frames were placed approximately 5 meters outside of a randomly selected island, in different directions. In each of the six reference plots outside of the project area, we randomly placed an additional ten frames.

We also measured aerial plant cover with line-point intercept at three randomly-generated points within the (treated) study area. Three evenly spaced 50-m transects radiated from each point in a “spoke” design (450 m of transects total) and were sampled before the study began in 2019 and after project implementation in the summer of 2020.

Statistical analysis

To determine the effect of treatment (tubeling vs. wildling) on sagebrush survival (live or dead), we used separate generalized linear mixed models with an observation-level random effect to analyze the June 2020 and October 2020 datasets (R package glmmTMB) (Brooks et al. 2017). Five wildling individuals were excluded from analysis as they were determined to not be subspecies *A. tridentata ssp. vaseyana.*

To determine which covariates were associated with tubeling mortality, we ran binomial generalized linear mixed models (R package glmmTMB) on several predictor variables separately. Each model used status of tubelings (live or dead) recorded during October 2020 assessments as the response variable. The predictor variables that were recorded at the time of planting included presence/absence of air pockets or exposed roots at the time of planting (“bad planting”), frost-heaving (presence/absence), physical damage (presence/absence), more than one plant growing together (presence/absence), and height of plants (cm).

To examine plant community composition of the seeded treatment plots we performed non-metric multidimensional scaling (NMDS; R package vegan; maximum of 100 random starts, 4 dimensions) on 0.25 m^2 frequency frame data from all islands in the seeded, tubeling and wildling treatments (n= 48 islands per treatment). We removed all species that occurred fewer than 10 times across all islands and excluded all unidentifiable species. To examine associations between plant community composition and the establishment of sagebrush from wildling, tubeling and seeding treatments we extracted NMDS axis 1 and 2 scores and used them as the predictor variables in a general linear model with a Poisson distribution (R package stats). We ran this model for each treatment with the number of surviving plants (tubeling and wildling) or number of seedlings (seeding) for each island as the response variable.

We used R (version 4.0.0) for all statistical analyses (R Core Team 2020). The seeding treatment, which was established for future comparisons to tubeling/wildling treatments, was not statistically compared to one-year tubeling or wildling survival in the present study.

RESULTS

Tubelings vs. wildlings

There was a statistically significant difference in survival outcomes between tubeling and wildling treatments for the both June 2020 and October 2020 (June chi square = 111.9, $p < 2.2\ e^{-16}$; Oct. chi square =114.8, $p < 2.2\ e^{-16}$; Table 2). In the summer of 2020, approximately six months after planting, mean probability of survival was 92% for wildlings, compared to only 17% survival for tubelings (Table 2). Six months later (October 2020), one-year post-planting, the mean probabilities of survival were similar: 91% and 16%, respectively for wildlings and tubelings (Fig. 3, Table 2). Most mortality occurred between fall planting and the first June post-planting; by June, 78% of tubelings (945 of 1200) and 9% of wildlings (116 of 1195) had died. Only an additional 5% (13 of 254) tubelings and 0.5% (6 of 1079) wildlings died between June and October (one-year post-planting), which encompassed the pronounced summer dry period. Based on one-year survival rates, wildlings yielded an average density of 0.4 plants per m^2 and the tubelings yielded an average density of 0.089 plants per m^2.

Live tubelings, measured within five weeks of planting, varied in height from 2 to 23 cm tall with a mean of 12.5 cm (±1 SE = 0.09) and had a mean crown area of 27.6 cm^2 (±1 SE = 0.62) (Fig. 4). The subset of wildlings (n = 297) measured within five weeks of planting, ranged in height from 6 and 25 cm tall with a mean height of 14.3 cm (± 1 SE =0.21) and a mean crown area of 35.3 cm^2 (± 1 SE =1.29) (Fig. 4). In June 2020, when all wildlings were assessed, heights ranged from 6 to 70 cm with a mean height of 21.3 cm (± 1 SE = 0.16) and mean crown area of 129.1 cm^2 (±1 SE = 2.43) (Fig. 4). The wildlings that were assessed in both Fall 2019 and June 2020 had an average growth increase of 9.0 cm between the two assessments.

Tubeling mortality

We found that 64% of tubelings experienced “bad planting” (i.e., roots being exposed or air pockets). These plants had only a 12% mean chance of survival in the first year whereas the remaining tubelings without “bad planting” had a nearly twice that, 23% mean chance of survival on average (Table 4). During the first assessment five weeks post-planting we also found that 19% of all tubelings experienced frost-heaving, 8% had more than one plant growing in the same container, and 10% experienced physical damage. None of these factors, nor tubeling height were found to be a significant predictor of first-year tubeling mortality (Table 4).

Seeding and control plots

The average establishment for sagebrush in the seeding treatment plots in July 2020 was 7.6 seedlings per m^2. By October of 2020, the mean density had declined to 5.2 seedlings per m^2. There was only one sagebrush individual recorded in frequency frames sampled within the control (unseeded, unplanted) plots.

Community composition

At least seventy-six unique species were identified in the treated project area in July 2020 (Table 5). Between 2019 (prior to project installation but after the initial seedbed prep of disking and harrowing) and 2020 (after project implementation) annual forb cover increased by 32.9% (Fig. 5). This increase can largely be attributed to the dominance of *Thlaspi arvense*, an exotic annual forb that commonly “pioneers” disturbed soils (Warwick et al. 2002) and occurred in 98% of nested frequency frames in July 2020.

We found that plant community composition (NMDS 1) was a significant predictor of number of sagebrush plants in tubeling and seeding treatments (Fig. 6, Stress = 0.19, R^2=0.97; tubeling Z = 5.8, p = 6.48e-09, seeding Z = 4.6, p= 4.01e-06). Notably, the species that were negatively related to NMDS 1 and also associated with low sagebrush survival / emergence, included species that were present in the project area prior to seedbed preparation and in the adjacent (untreated) reference area (Table 5). Most of the species that were positively related to NMDS 1 and associated with higher sagebrush survival / emergence were species that were included in our seed mix that was drill-seeded in the fall of 2019 (Fig 6.). NMDS2 was not a significant predictor for tubeling or seeding treatments (tubeling Z= 0.32, p= 0.75, seedling Z = 1.1, p= 0.28). Neither NMDS axis was significant for the wildling treatment (NMDS axis 1 Z= 0.78, p= 0.44; axis 2 Z = 0.96, p= 0.34), likely due to the high survival overall of wildling plants.

DISCUSSION

There is increasing need to restore degraded dryland ecosystems across the globe, but the conditions of these drylands often limit success of traditional restoration methods such as broadscale seeding. There is a need for innovation in this field of research both in approach to native plant establishment (e.g., use of plant materials that bypass the seedling establishment bottleneck) and in expanding the scope of where restoration efforts are focused (e.g., dryland pastures or areas with higher annual precipitation where potential for successful restoration is higher). Here we show that, when restoring dryland pasture, wildlings, mature plants that are transplanted with an intact rootball, can be used to achieve high rates of first-year establishment for mountain big sagebrush (*A. tridentata ssp. vaseyana*).

Tubeling vs. wildling survival

Our results illustrate that, when conditions are appropriate, transplanting mature sagebrush plants (“wildlings”) has potential to be a highly successful method of establishment. Many studies using tubelings have concluded that survival within the first year is a major barrier to establishment of sagebrush (Dettweiler-Robinson et al. 2013; Uselman et al. 2018; Brabec et al. 2015). Using wildlings instead of tubelings may overcome the survival bottleneck that occurs in this first year. We found that mean chance of first-year survival was 91% for wildling plants. Our findings align with previous studies that found relatively high (71-90%) survival can be achieved for sagebrush wildlings when correct transplanting techniques are used (Shumar & Anderson 1987; McArthur & Plummer 1978; McArthur 2004).

In contrast to wildling survival, we had relatively low survival rates (16%) for tubelings in our study. Although other studies have had considerable success using sagebrush tubelings, success rates tend to be variable (Clements & Harmon 2019; Epps & McKell 1983; Newhall et al. 2011; Dettweiler-Robinson et al. 2013; Stevens et al. 1981; Davidson et al. 2019; Davies et al. 2020). For example, Newhall et al. (2011) found 96% first year survival for mountain big sagebrush tubelings in an experimental garden outside Nephi, Utah, which then dropped to 68% and 12% survival, respectively, in plots with and without herbicide application by the fifth year. In contrast, Stevens et al. (1981) achieved only 13% average survival by the end of the first growing season when transplanting mountain big sagebrush and other containerized stock (size not specified), which the authors attributed to the poorly developed root systems within the containers. In a literature review examining the success of plantings of a different sub-species, Wyoming big sagebrush (*A. tridentata wyomingensis*) the mean survival rate for tubelings by the third year was 30% (range 4-67%) (Dettweiler-Robinson et al. 2013).

We found only one other study that directly compared tubelings vs. wildlings of sagebrush plants (McAdoo et al. 2013), but it was for a different sub-species Wyoming big sagebrush (*A. tridentata spp. wyomingensis*). McAdoo et al. (2013) compared Wyoming big sagebrush tubelings and wildlings across sites with varying community composition and found that tubelings planted in the first year of the study yielded nearly three times the density of established plants compared to wildlings. But for the second planting year there were no significant differences in density between tubelings and wildlings. The authors hypothesized that these patterns were driven by higher quality (i.e., size) of tubelings and wildlings in years one and two, respectively. The authors considered the density at which the Wyoming big sagebrush tubelings established two years after planting, an average of 1.6 ± 0.8 tubeling individuals per 10 m^2, a success (McAdoo et al. 2013). This establishment rate was nearly twice as high as our tubeling establishment, 0.89 individuals per 10 m^2, despite mountain big sagebrush typically having higher germination and establishment rates than Wyoming big sagebrush.

Factors influencing tubeling and wildling success

Consistent with our results, tubeling survival is known to be affected by the planting process (Landis & Dumroese 2010; Adams & Patterson 2004), whereas wildlings, particularly those that are transplanted with soil and root ball, may be more resistant to these problems. In our study, plantings were completed by vegetation crew members from a reputable contractor, which is standard practice for ecological restoration projects. Explicit directions on how to "correctly" plant were given, but covariates associated with poor planting quality were nonetheless significant predictors of tubeling mortality. In the weeks following planting, we found that many tubelings had roots exposed aboveground or had large air pockets in the soil around the plant. Plant roots are sensitive both to light and cold and can quickly desiccate when roots are exposed, leading to rapid mortality. When there are air pockets in the soil around the plant the roots, they are unable to uptake necessary water and nutrients and can quickly become desiccated (Stevens 1994). Tubelings that were planted well (i.e., for which we did not record any "bad planting" qualities) had nearly twice the chance of survival relative to poorly planted tubelings (23% vs. 12%). An advantage of wildlings is that, although the tap root may be severed when harvesting mature plants for transplant, the majority of the roots are left intact within the transplanted soil and good root-to-soil contact remains.

Another factor that may have reduced tubeling survival was our choice of planting equipment. Although quick, common and easy to use, dibbles may not be the best tool for planting tubelings, especially in soils with higher clay content, as they compact the surrounding soil when creating a hole. This compaction can limit root expansion and does not provide surrounding loose soil to cover the top of the tubeling (Landis & Dumroese 2010). Using this tool, in combination with a relatively young vegetation crew that experiences high turnover rates, may have contributed to tubeling mortality. Additionally, tubelings were left outside on-site for 10 days during planting in open-air crates, and direct sunlight and exposure to wind may have desiccated the plants and stressed them prior to planting (Landis & Dumroese 2010). Comparatively, wildlings were planted the same day that they were harvested and the plants were wrapped in burlap during transportation to prevent desiccation.

Notable for comparisons of tubeling vs wildling plantings, is that the identity of who carries out the plantings may ultimately affect success rates. Researchers often rely on planting by research teams or students, who may feel a greater accountability to the research process and typically are charged with planting fewer plants than in a real-world ecological restoration setting. Thus, research studies could fail to capture the true mortality rates that occur on landscape-scale restoration projects where large, hired field crews are responsible for implementation. Our study relied on hired vegetation crew members who are contracted for ecological restoration projects and therefore have a greater need (than researchers) to balance planting quality with speed and productivity.

Use of wildlings may afford practitioners greater control over quality of plant materials. When planting wildlings, practitioners can scout out in advance and then select for plants of a certain size or vigor at the time of implementation, whereas quality of greenhouse stock can often be variable, with practitioners not knowing the overall quality until project implementation begins. In our case, although height was not a significant predictor of tubeling survival, the low overall quality of the lot of tubelings we used may have nonetheless contributed to our overall low survival rates (Grossnickle 2012; Landis & Dumroese 2010). Our tubelings were grown from seed that was considered by the grower to be “less than ideal” in quality, with only 13% purity, which resulted in fewer plants germinating in containers than expected. The grower then re-seeded the tubes at a later date to compensate for the lack of germinates, meaning a portion of the greenhouse stock was younger and potentially poorly rooted at the time of planting (Jeff Rebernak, personal communication 2021). This is not uncommon for restoration projects, in which growers are given a limited timeframe to produce plants and often must start growing stock at a time that is out of sync with the natural growing sequence for the species, which can result in lower quality plants.

Our assessment of tubeling and planting size at the time of planting allowed us to quantify the high variability and low quality of some of our planting materials. Yet, often studies using containerized stock do not assess the quality of individual plants prior to planting, making it difficult to draw conclusions about physical traits that may affect survival (Dettweiler-Robinson et al. 2013). At least one study of containerized plants of other species found containerized plants to have deformed root systems or roots poorly adapted to natural field soil conditions (Young & Evans 2000). More closely examining individual plant traits (e.g., root to shoot ratios) could provide insights into less obvious components of tubeling quality and characteristics that yield better restoration outcomes, especially in plants grown from locally-adapted seed (Brabec et al. 2015; Leger & Baughman 2015; Rowe & Leger 2012). Additionally, more closely examining traits of wildlings (e.g., size, vigor) at the time of harvest and then monitoring their survival over time will provide insights as to which qualities to select for during harvest, as well as which qualities may increase long-term success.

Harvesting our wildlings close to the project site (approximately seven miles away) may have also contributed to our high survival rates. McArthur and Plummer (1978) reported a mean establishment rate of 78% (range of 43% to 100%) one year after planting wildlings from nine different source populations of mountain big sagebrush. Although the lowest one-year survival rate in their study (43%) was still relatively high, the variability (mean 78%, range of 43% to 100%) in survival suggested that sourcing wildlings from nearby or climatically-similar populations is crucial in maximizing survival outcomes (McArthur & Plummer 1978). Use of local plant materials is a commonly recommended seed-sourcing guideline (e.g., working within seed transfer zones) both for direct seeding and for growing greenhouse plants (McArthur 2004; Meyer 2008; Appendix A). Local adaptations can result in higher drought or frost resistance, increased growth rates, and higher competitive advantage compared to plants that are not locally-adapted (Meyer 2008). Furthermore, when using locally-collected wildlings the plants have the same advantageous traits that locally-adapted seed/tubelings have, but the added benefit of having already faced natural filtering from local environmental and community conditions, perhaps making them even more resilient (Meyer 2008).

Matching planting methods and materials to environmental attributes and conditions is an important factor in the success or failure of any restoration project. We chose to plant in the fall when precipitation was anticipated. In a study comparing fall and spring plantings of containerized Wyoming big sagebrush plants, Clements and Harmon (2019) found that fall transplanting success (average survival of 65%) was significantly higher than spring transplanting success (average survival of 41%) across three years of plantings. In a different study, Newhall et al. (2011) attributed the rapid decline in survival of mountain big sagebrush wildlings post-planting (from 96% to 12% over four years) to the dryness of the study site which was unsuitable for the *vaseyana* subspecies. While some of these variables are often out of the control of practitioners, when possible, they should nonetheless be taken into consideration to increase the likelihood of establishment from plantings.

Transplants as an alternative to seeding

The NRCS plant guide for big sagebrush (regardless of subspecies) recommends a target density of 400 sagebrush plants per acre (0.099 plants per m^2) to provide habitat for sagebrush-obligate species (Tilley et al. 2008). Survival rates from our tubeling treatment one year after planting (0.089 plants per m^2) strongly suggests that target will not be met. In contrast, assuming low to moderate mortality after the first year, our wildling treatments are poised to meet or exceed that target with a one-year post-planting density of 4x the target density (0.400 plants per m^2).

We seeded sagebrush at a rate (0.5 lbs pls per acre) that falls within the recommended range for establishing sagebrush stands but is higher than what is commonly used by practitioners. This high seeding rate may have played a role in our high emergence rate within the first year (average density of 5.2 plants per m^2) as it is well-documented that seeding at high rates can increase establishment, especially when propagule limitation is a concern (Williams et al. 2002; Barr et al. 2017). Our decision to seed in the fall, which is the recommended season for seeding (Lambert 2005; Meyer 2008), likely played a significant role in our success (Brabec et al. 2015; Appendix A). Continued monitoring will be necessary to determine whether these high initial seedling densities lead to high establishment as the seedlings proceed through the bottleneck limitations of first-year survival (Dettweiler-Robinson et al. 2013; Uselman et al. 2018; Brabec et al. 2015).

Regardless of survival rates, plants that establish from seed have some notable benefits compared to containerized plants. Welch (1997) compared seed-derived plants to container-derived plants of mountain big sagebrush and found that the former had lower mortality rates, produced more seeds, had larger crowns, and deeper and more developed root systems. The mechanisms behind these outcomes are not yet fully understood but this is an observation seen across many studies, especially those using woody species (Welch 1997; Young & Evans 2000; McCreary 1995). Researchers hypothesize that this lower growth rate seen in containerized plants is due to restriction in the plants' tap root (Pyke et al. 2020). Plants grown from seed also avoid the potential root deformation problems that can form when plants are grown in containers (Young & Evans 2000). These benefits of seed-derived plants may also hold true for wildlings, however, we found no existing literature comparing growth or seed production rates of plants derived from seed versus wildlings. Although the wildlings in our study seem to have adequately developed roots, we will need to monitor these individuals over time as their roots expand out of the transplanted soil and into the native soil on site. Tracking the heights of individual plants from tubeling, wildling and seeded treatments over time would provide more insight about how the growth and reproductive rates vary between establishment methods.

Cost comparison

Costs of ecological restoration projects are rarely tracked (Munson et al. 2020), and when they are, the costs are typically calculated based on cost per area or based on amount of seed distributed or number of plants installed on a site (Palma & Laurance 2015). A more informative approach is to calculate cost per established plant. Based on our records, we estimate that it took approximately 8 minutes to harvest one wildling and approximately 4 minutes of planting time (this estimate includes loading, transportation and unloading). The conditions for harvesting and planting were relatively challenging in this study as the ground was often partially frozen. Comparatively, it took only about 30 seconds to plant each tubeling, similar to McAdoo et al. (2013). Thus, it took 24 times longer to plant wildlings but survival was only 4.5 times as high. Yet, despite the labor being considerably higher for wildlings, when considering the cost per surviving plant, our estimated average cost of wildlings was less than half of the estimated average cost of tubelings ($3.33 for wildlings; $7.35 for tubelings) (Table 7). The cost-effectiveness of wildlings could be even higher under easier working conditions. For example, McAdoo et al. (2013) estimated that it took only 20 seconds to harvest each wildling and 30 seconds to plant them. Their plants were harvested from the roadside in the spring and may be more representative of easier harvesting conditions. Costs of tubelings also may be reduced by using smaller containers (there is often no significant difference in survival of plants in small versus large containers; (Palmerlee & Young 2010; Dumroese et al. 2009; Dettweiler-Robinson et al. 2013; Young & Evans 2000) and by producing great quantities of stock to reduce "nursery care" (Dettweiler-Robinson et al. 2013; Pérez et al. 2019).

Restoration of dryland pastures

Restoring dryland pastures to return ecosystem function and services to a landscape will be increasingly important as global abandonment of agricultural lands increases. The conditions present in these types of areas (e.g., dominance of weedy species, lack of soil crusts, low nutrient availability, compaction.) create additional challenges for restoration and may require higher than typical involvement in seedbed preparation and herbicide use. While more extensive than what would be done in a wildland setting, our preparation of the soil, herbicide application, use of drill-seeding, or some combination thereof was effective in reducing cover of perennial grasses (from 41% pre- to 4% post-treatment). The effectiveness of that seedbed preparation in turn appeared to affect sagebrush establishment; our NMDS analyses indicate that sagebrush establishment was higher in in areas where species from our seed mix established, and lower in areas where species persisted in the seedbank from prior to project implementation.

MANAGEMENT IMPLICATIONS

In order to determine which method of establishment is appropriate for a project there are several considerations (i.e., scale, costs, labor, feasibility of preparation and implementation) that land managers must consider (Fig. 6). Our study highlights considerations for managers wishing to use tubelings regarding both the quality of the plant material and the planting process. Our study also supports the idea that older plants (wildlings) that have already faced various environmental filters and more developed root systems have a greater chance of survival. In addition, though untested by us, transplanting with a soil ball intact may increase survival rates relative to bare-root plantings and should be considered when using this method for establishment.

There are several potential advantages of wildlings over tubelings in addition to their higher survival rates. Wildlings have the additional benefit of producing seed on-site sooner than tubelings. One year after planting, 6% of wildlings (64 individuals) in our study were reproducing compared to only one tubeling. Microsites underneath the crowns of sagebrush provide more advantageous conditions for seedlings, therefore planting larger sagebrush, such as wildlings, may help facilitate additional establishment of seedlings (Monsen et al. 2004; Holthuijzen & Veblen 2015).

We therefore recommend considering wildlings with the following caveats:

1. The scale of a project is one of the biggest factors that would influence method selection. Projects that are focused on restoring a large area of land or land that is relatively inaccessible may find that seeding is the only reasonable restoration approach.

2. To use wildlings, it is necessary to have an intact stand near the target field site. For this project we had permission to harvest wildlings from nearby private property. Projects using wildlings may need to go through a permitting process to harvest from nearby lands. Working with state, federal or private landowners will be necessary to obtain necessary permissions to collect wildlings for similar projects.
3. The decision of when to harvest and plant wildlings, plant tubelings or perform seeding should be dependent upon anticipated precipitation and soil moisture at the harvest and target locations. This study was conducted at a high elevation area with relatively high precipitation. Successful seedings typically occur in areas that receive more than 30.5 cm of mean annual precipitation (Pilliod et al. 2017). Plantings and seedings in the Intermountain West should take place when temperatures and risk of frost heaving are low and soil moisture and chance of rainfall are high (Shaw et al. 2005; Meyer 2008; Shriver et al. 2018). McAdoo et al. (2013) also hypothesized that soil conditions at the time of harvest play a role in survival of wildlings as dry soils led to increased root tearing.
4. It is well-established that there is a correlation between glyphosate application and survival of sagebrush as well as glyphosate and suppression of smooth brome (McAdoo et al. 2013). Practitioners should consider application of herbicide prior to installing plants on site to reduce competition from introduced and invasive species. McAdoo et al. (2013) found that application of glyphosate prior to planting has the potential to increase survival of transplants up to 300%.

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TABLES AND FIGURES

Table 1. Twenty-two rangeland species included in herbaceous seed mix.

	Scientific name	**Common name**	**Nativity status**	**State of origin**	**lbs pls/acre**
Perennial grasses	*Achnatherum lettermanii*	Letterman's needlegrass	Native	MT	0.5
	Bromus marginatus	Mountain brome	Native	ID	1
	Festuca idahoensis	Idaho fescue	Native	ID	0.5
	Festuca ovina	Sheep fescue	Introduced	OR	1.25
	Leymus cinereus	Basin wildrye	Native	ID	0.2
	Pascopyrum smithii	Western wheatgrass	Native	ID	1.5
	Poa secunda	Sandberg bluegrass	Native	WA	0.25
	Pseudoroegneria spicata	Bluebunch wheatgrass	Native	ID	1.8
Perennial forb / subshrub	*Achillea millefolium*	Western yarrow	Native	ID	0.1
	Astragalus cicer	Chickpea milkvetch	Introduced	MT	0.75
	Cleome serrulata	Rocky Mountain beeplant	Native	UT	0.85
	Gaillardia aristata	Blanketflower	Native	OR	0.25
	Linum perenne	Blue flax	Introduced	ID	0.1
	Lomatium dissectum	Fernleaf biscuitroot	Native	UT	0.1
	Lomatium triternatum	Nineleaf biscuitroot	Native	UT	0.2
	Lupinus sericeus	Silky lupine	Native	UT	0.1
	Medicago sativa	Alfalfa	Introduced	MT	1
	Onobrychis viciifolia	Sainfoin	Introduced	ID	2
	Penstemon strictus	Rocky Mountain penstemon	Unreported	UT	0.1
	Ratibida columnifera	Upright prairie coneflower	Native	OR	0.1
	Solidago canadensis	Canada goldenrod	Native	ID	0.1
	Sphaeralcea coccinea	Scarlet globemallow	Native	UT	0.1

Table 2. Estimated marginal means from generalized linear mixed models for tubeling and wildling survival data for June 2020 and October 2020.

Means estimate on proportion scale (DF = 21)				
Treatment	**Probability**	**SE**	**Lower CL**	**Upper CL**
June 2020				
Tubeling	0.171	0.037	0.107	0.262
Wildling	0.917	0.021	0.863	0.951
October 2020				
Tubeling	0.16	0.035	0.1	0.247
Wildling	0.911	0.021	0.855	0.946

Table 3. Estimated marginal means from binomial generalized linear mixed models examining possible associations between variables and tubeling mortality (* indicates statistical significance at the 0.05 level).

Means estimate on proportion scale (DF = 1197)					
Covariate	**Level**	**Estimate**	**SE**	**Lower CL**	**Upper CL**
Bad Planting *	Absent (0)	0.227	0.558	0.136	0.354
	Present (1)	0.119	0.033	0.068	0.199
Heaved	Absent (0)	0.153	0.044	0.085	0.260
	Present (1)	0.162	0.051	0.084	0.289
More Than One	Absent (0)	0.151	0.042	0.085	0.254
	Present (1)	0.203	0.065	0.104	0.359
Physical Damage	Absent (0)	0.151	0.043	0.084	0.256
	Present (1)	0.192	0.063	0.096	0.345
Means estimate on logit scale					
Height	-	-0.009	0.027	-	

Table 4. Traits of tubelings and wildlings planted in October 2019 within 5 weeks of planting, the summer following planting (June 2020), and one-year post-planting (October 2020). Means ± 1 SE are displayed for the three continuous variables, vigor, height, and crown. The remaining are ordinal (yes/no) variables. Far right column lists statistical results for variables that were tested as predictors of 1-year (Oct. 2020) tubeling survival.

Trait	**Oct / Nov 2019**		**June 2020**		**Oct 2020**		**1-year tubeling mortality**	
	Tubeling	Wildling	Tubeling	Wildling	Tubeling	Wildling	Chi-square	p
% Alive	95% (1137 of 1200)	100% (1197 of 1197)	21% (254 of 1200)	90% (1079 of 1197)	20% (242 of 1200)	90% (1073 of 1197)	--	--
Vigor†	41 ± 0.94 %	63 ± 0.21%	87 ± 0.92%	88 ± 0.35%	80 ± 1.16%	83 ± 0.43%	--	--
Height†	12.5 ± 0.09 cm	14.3 ± 0.21 cm	-	21.4 ± 0.16 cm	-	-	-0.319 (z-value)	0.749
Crown Area†	26.8 ± 0.62 cm^2	35.0 ± 1.28 cm^2	-	129.3 ± 2.43 cm^2	-	-	--	--
% Frost Heaved	19%	0%	-	-	-	-	0.099	0.9
% "Bad Planting"	64%	2%	-	-	-	-	20.6	5.7e^{-06}
% Physical Damage	10%	1%	-	-	-	-	1.256	0.263
% > 1 Plant	8%	5%	-	-	-	-	2.105	0.147
% Reprod-uctive†	0%	0%	0%	0%	0.40%	6%	--	--
Insect Damage	-	12%	0%	35%	0%	15%	--	--
Rodent Damage	-	-	3%	1%	0.01%	0%	--	--

† Denotes percentage of live plants only, otherwise percentage is of all plants (dead or alive).

Table 5. Frequency of all species recorded in 0.25m^2 frequency frame sampling of project area (n = 420) and adjacent reference area (n=60) in July 2020. Species included in seed mix are bolded. (* constitute groupings of several species that were unidentifiable at the time of sampling because plants were newly established and did not have any reproductive features).

Species code	**Scientific name**	**Average frequency %**	**Standard error ±**
Project area			
THAR	*Thlaspi arvense*	97.6	0.82
PODO	*Polygonum douglasii*	92.6	1.41
COTI	*Collomia tinctoria*	91.7	2.01
TAOF	*Taraxacum officinale*	65.0	4.51
POSE	***Poa secunda***	57.9	3.88
UG	*Unidentified grass*	43.3	4.45
ACMI	***Achillea millefolium***	42.6	3.49
VEPE	*Veronica peregrina*	41.9	4.75
POBU	*Poa bulbosa*	38.8	4.70
UF	*Unidentified forb*	36.0	4.20
BRIN	*Bromus inermis*	31.4	2.65
MESA	***Medicago sativa***	29.3	3.00
COLI	*Collomia linearis*	28.6	4.21
Lupine	***Lupine spp.***	27.9	3.08
DRVE	*Draba verna*	27.4	3.56
CHAL	*Chenopodium album*	24.8	2.98
ELTR	*Elymus trachycaulus*	23.3	3.12
MELU	*Medicago lupulina*	23.1	3.00
FEID	***Festuca idahoensis***	22.1	3.30
ARTR	*Artemisia tridentata*	21.0	4.43
RATE	*Ranunculus testiculatus*	20.2	4.05
ACHY	*Achnatherum hymenoides*	16.2	3.30
ONVI	***Onobrychis viciifolia***	15.5	1.71
ALDE	*Alyssum desertorum*	15.5	3.13
Elymus	*Elymus spp.*	14.5	2.32
POAV	*Polygonum aviculare*	13.8	2.15
Hedysarum	*Hedysarum spp.*	13.8	2.34
CIAR	*Cirsium arvense*	13.8	1.96
PEST	***Penstemon strictus***	12.9	1.75
PSSP	***Pseudoroegneria spicata***	11.4	2.56

LASE	*Lactuca serriola*	11.0	1.98
LIPE	***Linum perenne***	10.7	1.58
ALPR	*Alopecurus pratensis*	10.0	1.74
ELRE	*Elymus repens*	9.3	2.63
TRDU	*Tragopogon dubius*	8.3	1.40
RACO	***Ratibida columnifera***	8.3	1.44
CHBO	*Chenopodium botrys*	8.3	2.07
Festuca	*Festuca spp.*	7.9	2.14
POPR	*Poa pratensis*	7.4	1.81
Sporobolus	*Sporobolus spp.*	6.4	1.66
GARA	*Gayophytum ramosissimum*	5.7	2.02
Bromus	*Bromus spp.*	5.0	1.46
HECO	*Hesperostipa comata*	5.0	2.19
ANPA	*Antennaria parvifolia*	4.5	0.91
NEBR	*Nemophila breviflora*	4.5	2.51
ARLU	*Artemisia ludoviciana*	4.0	1.08
Poa	*Poa spp.*	4.0	1.32
SYAS	*Symphyotrichum ascendens*	3.6	1.56
VETH	*Verbascum thapsus*	3.6	1.61
CABU	*Capsella bursa-pastoris*	2.9	0.85
Oenathara	*Oenothera spp.*	2.1	1.39
LIVU	*Linaria vulgaris*	2.1	0.94
CHLE	*Chenopodium leptophyllum*	1.9	0.98
VIAM	*Vicia americana*	1.7	0.59
Arabis	*Arabis spp.*	1.2	0.78
CLSE	***Cleome serrulata***	1.2	0.61
MAMA	*Matricaria matricarioides*	1.2	0.61
EREA	*Erigeron eatonii*	1.0	0.46
Rumex	*Rumex spp.*	1.0	0.75
ASMI	*Astragalus miser*	0.7	0.53
Cryptantha	*Cryptantha spp.*	0.7	0.53
Lotus	*Lotus spp.*	0.7	0.53
NA(BR)	*Navarretia (breweri)*	0.7	0.40
VIPU	*Viola purpurea*	0.7	0.53
ASCO	*Astragalus convallarius*	0.5	0.48
Claytonia	*Claytonia spp.*	0.5	0.33
Collinsia	*Collinsia spp.*	0.5	0.33
EQLA	*Equisetum laevigatum*	0.5	0.48
LOTR	***Lomatium triternatum***	0.5	0.33

Symphyotricum	*Symphyotrichum spp.*	0.5	0.33
Aster	*Aster spp.*	0.2	0.24
Cirsium	*Cirsium spp.*	0.2	0.24
COPA	*Collinsia parviflora*	0.2	0.24
Crepis	*Crepis spp.*	0.2	0.24
DISP	*Distichlis spicata*	0.2	0.24
Delphinium	*Delphinium spp.*	0.2	0.24
HOJA	*Hordeum jubatum*	0.2	0.24
LAOC	*Lappula occidentalis*	0.2	0.24
PHPR	*Phleum pratense*	0.2	0.24
SPCR	*Sporobolus cryptandrus*	0.2	0.24
Trifolium	*Trifolium spp.*	0.2	0.24
Reference area			
BRIN	*Bromus inermis*	98.3	0.02
POPR	*Poa pratensis*	75.0	0.12
TAOF	*Taraxacum officinale*	66.7	0.12
COTI	*Collomia tinctoria*	48.3	0.14
Lupine	*Lupine spp.*	46.7	0.15
ALPR	*Alopecurus pratensis*	45.0	0.09
POBU	*Poa bulbosa*	35.0	0.13
PHPR	*Phleum pratense*	23.3	0.12
PODO	*Polygonum douglasii*	23.3	0.11
ALDE	*Alyssum desertorum*	20.0	0.08
ACMI	*Achillea millefolium*	20.0	0.11
SYAS	*Symphyotrichum ascendens*	15.0	0.07
TRDU	*Tragopogon dubius*	15.0	0.04
CIAR	*Cirsium arvense*	13.3	0.10
ARTR	*Artemisia tridentata*	10.0	0.05
VEPE	*Veronica peregrina*	6.7	0.03
LASE	*Lactuca serriola*	3.3	0.02
UF	*Unidentified forb*	3.3	0.02
AGUR	*Agastache urticifolia*	1.7	0.02
COLI	*Collomia linearis*	1.7	0.02
GARA	*Gayophytum ramosissimum*	1.7	0.02
HEOC	*Hedysarum occidentale*	1.7	0.02
LAOC	*Lappula occidentalis*	1.7	0.02
LIVU	*Linaria vulgaris*	1.7	0.02
MELU	*Medicago lupulina*	1.7	0.02
ORLU	*Orthocarpus luteus*	1.7	0.02

Table 6. Comparison of estimated costs for tubeling and wildling treatments. A $15/hr labor wage was used for this estimate.

		Tubeling	**Wildling**
Cost per plant	Greenhouse cost	$1.35	--
	Labor cost: Harvest	--	8 min (0.133 hrs) * $15.00/hr = $1.99
	Labor cost: Planting	0.5 min (0.008 hrs) * $15.00/hr = $0.12	4 min (0.067 hrs) *$15.00/hr = $1.01
	Total cost per plant	**$1.47**	**$3.00**
	# Planted	1200	1200
Project costs	Total planting cost	1200*$1.47 **= $1,764**	1200*$3.00 = **$3,600**
	Number surviving plants	242	1073
	Estimated cost per surviving plant	$1,764/242 plants = **$7.29**	$3,600/1073 plants **= $3.36**
	Associated costs excluded from analysis	Seed testing and cleaning, transportation from greenhouse to site, planting tools	Permit for harvesting, burlap, twine, planting tools

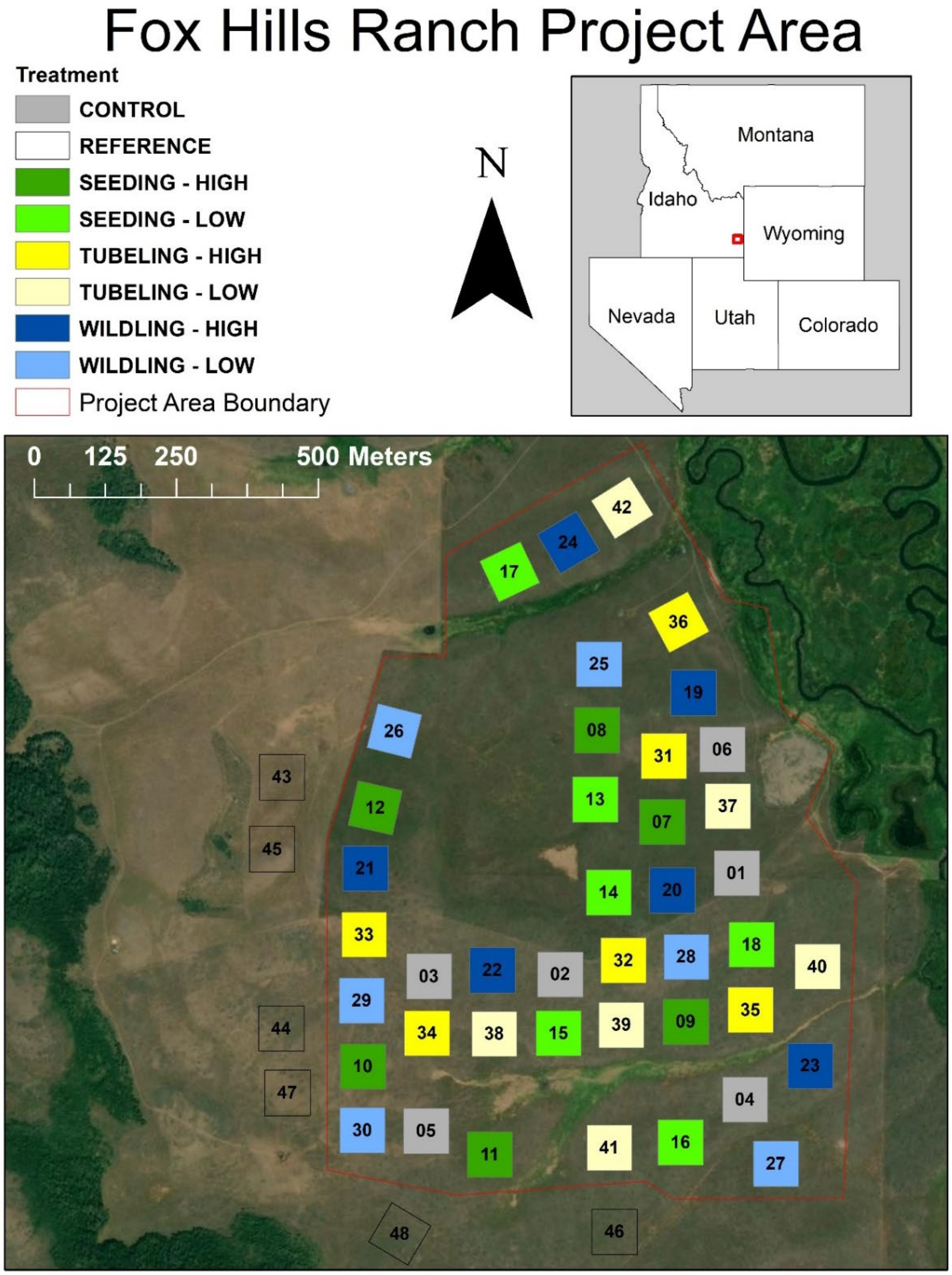


Figure 1. Research plot layout within project area at Fox Hills Ranch in Southeastern Idaho. Colored boxes (1-42) are 80 m x 80 m plots within the project area that were disced/harrowed/herbicided/seeded before applying sagebrush establishment treatments, and clear boxes (43-46) are untreated reference areas outside the project area. “High” and “Low” in the legend refer to arrange of the four sagebrush islands per plot in high vs low densities (see Fig. 2). The 80 m x 80 m plots were located a minimum of 15 m from each other.

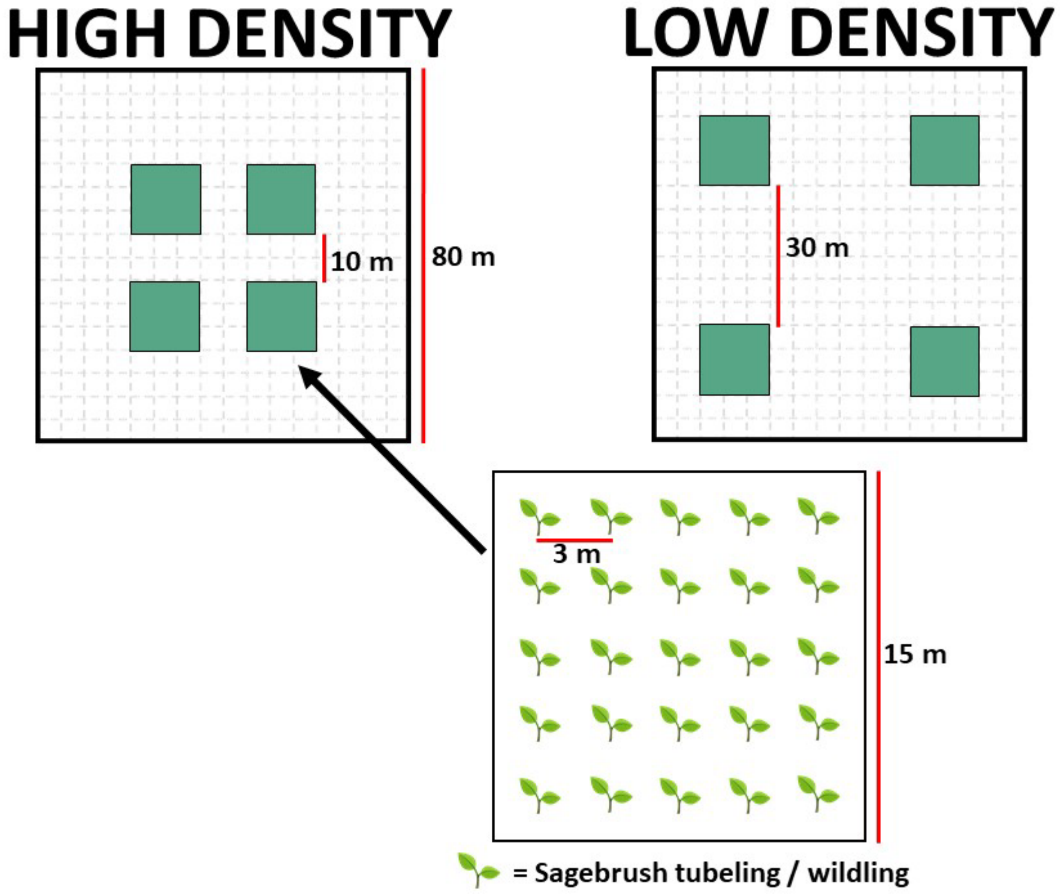


Figure 2. Layout of 80 m x 80 m experimental plots that each contain four 15 m x 15 m ‘islands’ arranged in either high (10 m apart) or low (30 m apart) densities. Twenty-five tubeling or wildling plants were planted within each island on a 3m-spaced grid. These densities were chosen as part of long-term research examining effect of island densities on long-term nucleation of sagebrush plant communities (sensu Hulvey et al. 2017).

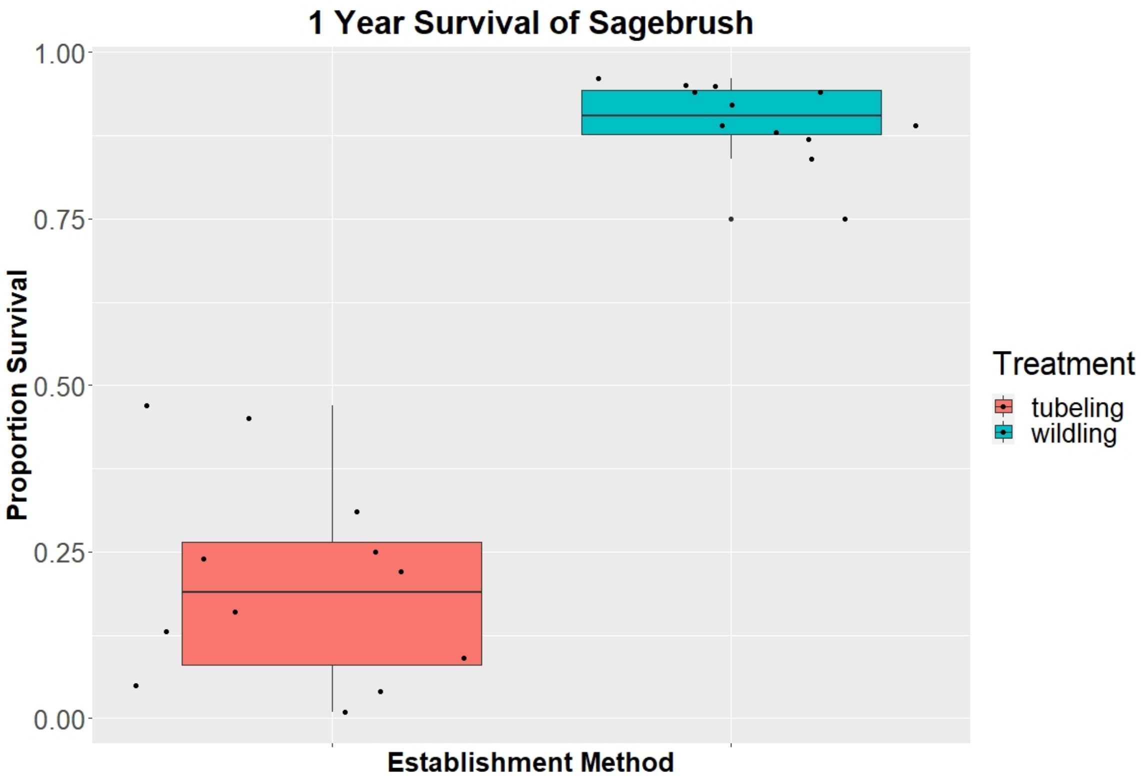


Figure 3. Proportion survival of tubeling and wildling sagebrush individuals one-year post-planting. Each box represents the interquartile range between the 25th percentile and 75th percentile for proportion of survival. The bold line in the middle of the box represents the median for proportion of survival. The whiskers extend in both directions to the minimum and maximum proportion survival.

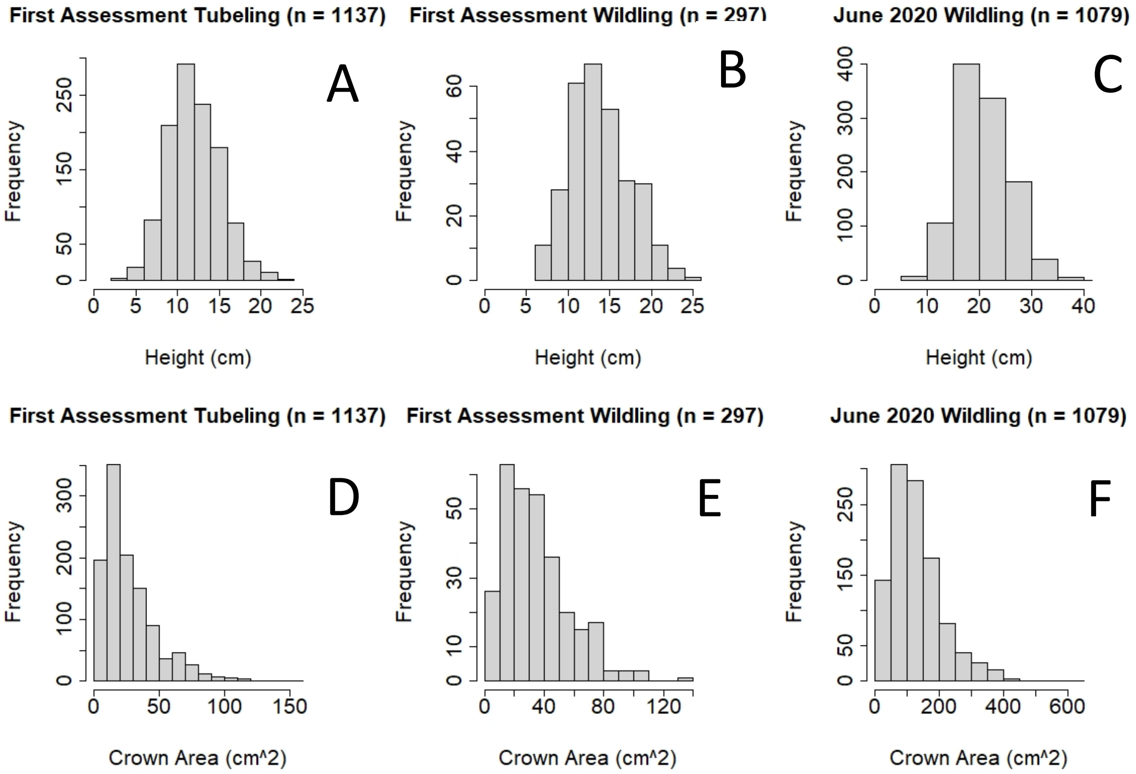


Figure 4. Sizes of tubeling and wildling sagebrush plants. Heights of (A) all live tubelings within 5 weeks of planting (Oct/Nov 20219, n = 1137) and (B) a subset of wildlings during Oct/Nov 2019 (n = 297), and (C) all surviving wildlings in June 2020 (n = 1079). Crown areas (D-F) for the same plants. Crown area estimated using ellipsoid calculation for area (A = π r1•r2) from field measurements.

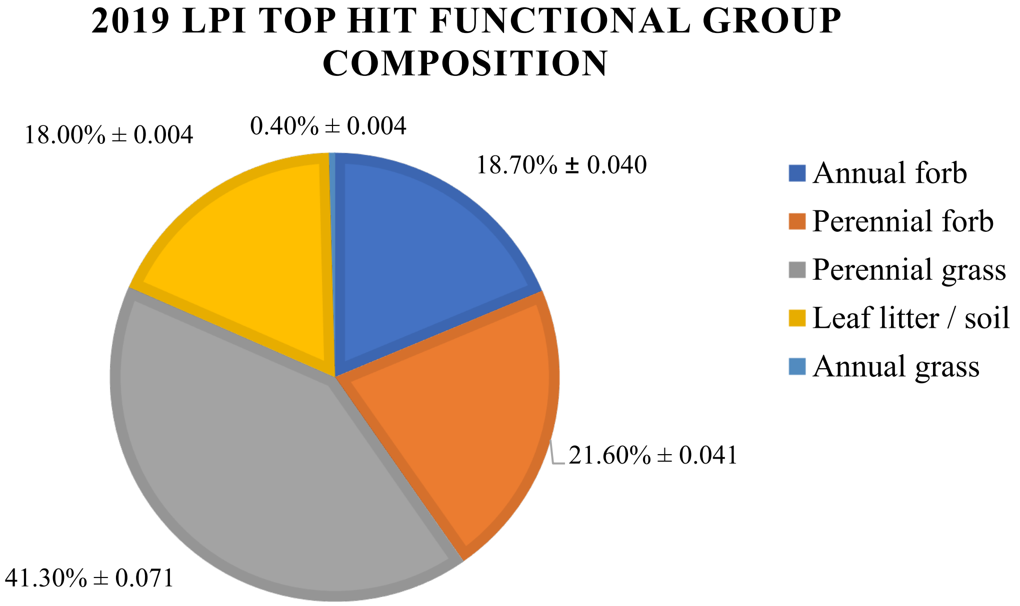


Figure 5. Average functional group composition across three points each with three radiating 50-m line-point intercept transects (450 m of transects total) prior to herbicide and project installation but after initial seedbed preparation in 2019 and during the first summer post-implementation in 2020.

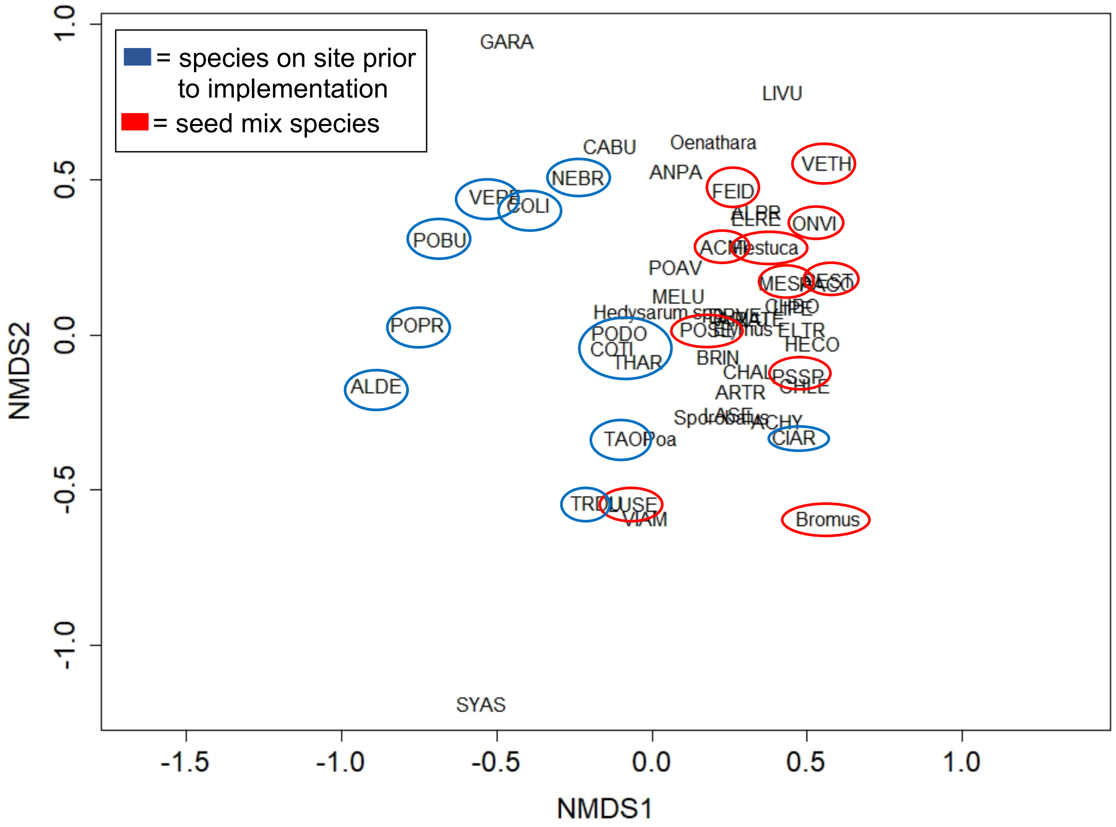
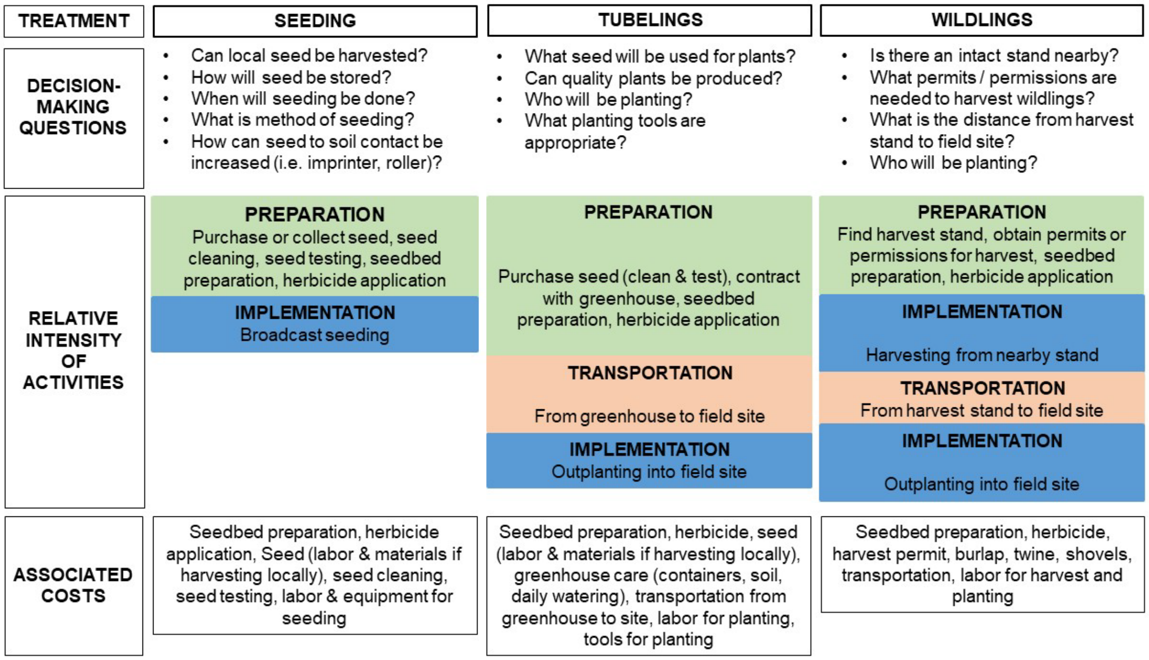


Figure 6. Plant species scores along NMDS axes 1 and 2 based on frequency frame data in the project area. Species circled in red were included in the herbaceous seed mix. Species circled in blue were recorded during our 2019 sampling prior to seed mix application. See Table 5 for species codes.



TREATMENT	SEEDING	TUBELINGS	WILDLINGS
DECISION-MAKING QUESTIONS	• Can local seed be harvested? • How will seed be stored? • When will seeding be done? • What is method of seeding? • How can seed to soil contact be increased (i.e. imprinter, roller)?	• What seed will be used for plants? • Can quality plants be produced? • Who will be planting? • What planting tools are appropriate?	• Is there an intact stand nearby? • What permits / permissions are needed to harvest wildlings? • What is the distance from harvest stand to field site? • Who will be planting?
RELATIVE INTENSITY OF ACTIVITIES	**PREPARATION** Purchase or collect seed, seed cleaning, seed testing, seedbed preparation, herbicide application **IMPLEMENTATION** Broadcast seeding	**PREPARATION** Purchase seed (clean & test), contract with greenhouse, seedbed preparation, herbicide application **TRANSPORTATION** From greenhouse to field site **IMPLEMENTATION** Outplanting into field site	**PREPARATION** Find harvest stand, obtain permits or permissions for harvest, seedbed preparation, herbicide application **IMPLEMENTATION** Harvesting from nearby stand **TRANSPORTATION** From harvest stand to field site **IMPLEMENTATION** Outplanting into field site
ASSOCIATED COSTS	Seedbed preparation, herbicide application, Seed (labor & materials if harvesting locally), seed cleaning, seed testing, labor & equipment for seeding	Seedbed preparation, herbicide, seed (labor & materials if harvesting locally), greenhouse care (containers, soil, daily watering), transportation from greenhouse to site, labor for planting, tools for planting	Seedbed preparation, herbicide, harvest permit, burlap, twine, shovels, transportation, labor for harvest and planting

Figure 7. Comparison of three methods of establishing sagebrush to assist land managers in decision making for restoration projects based on our project in a mountain big sagebrush site in southeastern ID.

APPENDIX

APPENDIX A

EXAMINING THE EFFECTS OF SEED SOURCE AND SEASON OF SEEDING ON MOUNTAIN BIG SAGEBRUSH ESTABLISHMENT

INTRODUCTION

Although there has been extensive research on how to maximize seeding outcomes for sagebrush, establishment from seeding remains highly unpredictable and largely unsuccessful (Pilliod et al. 2017; Knutson et al. 2014; Boyd & Davies 2012). Nonetheless, seeding of sagebrush remains the most common vegetation restoration method and therefore there is a continued need to improve seeding methods and materials as well as deepen our understanding of the factors that limit seeding success.

Coinciding with natural dispersion, fall is well-established as the ideal time to seed sagebrush (Meyer 2008). Although fall is the optimal season to seed, there is still significant risk that the seed will germinate early, i.e., that fall or in early winter, and be killed prior to spring. Conversely, when seeding in spring, it is unlikely that seeding can be accomplished in time to coincide with natural cycles of seedling emergence that occur immediately after spring snowmelt, or that soil moisture will provide adequate conditions to sustain germination and establishment of seedlings (Meyer 1994, 2008). This means there are challenges associated with both fall and spring seeding that may limit establishment.

However, there are several reasons why land managers might want to seed in the spring. First, many land managers are limited by strict time constraints and may have no choice but to seed in the spring to meet grant or project deadlines. Second, often land managers receive sagebrush seed in the winter after collection has been done in the fall, which means they either need to store the seed in appropriate conditions (temperature and moisture controlled) or use the seed in the spring. Third, the majority of research on sagebrush seeding has been conducted using Wyoming big sagebrush, which has more difficulty establishing from seed compared to Mountain big sagebrush. Spring sagebrush seedings are largely considered unsuccessful due to the lack of soil moisture but it is worth exploring whether it is feasible to seed mountain big sagebrush in the spring at a higher precipitation site (Meyer 1992).

One way to improve establishment from seed that has garnered a lot of recent attention is to use locally-collected seed from nearby populations rather than commercial seed from within the appropriate seed transfer zone (Meyer & Monsen 1992; Humphrey & Schupp 2002; Uselman et al. 2018; Walker et al. 2015). Plants derived from more site-specific seed may be more frost or drought tolerant, have higher growth rates, and express more advantageous flowering and germination patterns (Meyer 2008). However, land managers may not always have the time or resources to collect seed from nearby intact stands, especially in cases where wildfires have disturbed large swaths of land and there are few remaining stands to collect from. It is therefore important to identify the advantages, if any, of using local seed for improving restoration outcomes for seeding sagebrush.

Here we use a case study to experimentally test the effect of source (local vs. commercial) and season (fall vs. spring) on establishment of mountain big sagebrush from broadcast seeding.

METHODS

Experimental design

Dispersed throughout the study site (Fig. A.1) we established ten blocks each containing five 3 x 3 m plots, each assigned to one of five treatments: four factorial combinations of seed source (commercially-purchased vs. locally collected) and season of seeding (fall or spring) and a fifth control (no seeding) treatment. The local seed was collected from a wildland stand in the nearby Caldwell canyon approximately 7 miles from the ranch in October of 2019. Each plot was seeded at a density of 0.5 pure live seed per acre, which was calculated using purity and germination rate (Hoag et al. 2002). This seeding rate is on the higher end of what is the recommended rate for establishing sagebrush stands. The fall treatment was seeded by hand on top of approximately 12 cm of snow on December 6th, 2019. The spring treatment was seeded by hand directly on to soil on May 11th, 2020, shortly after snowmelt and as soon as the site was accessible, and a roller was used to increase seed to soil contact.

Data collection

Density of sagebrush seedlings was measured in July of 2020. Three 0.25 m^2 frames were randomly placed within each plot and the number of sagebrush seedlings within each frame were counted.

Statistical analysis

We employed a negative binomial general linear mixed model (package glmmTMB) to examine the effect of seed source and season on establishment of sagebrush seedlings (Meyer 2008; Shaw et al. 2005). We combined the sum of all seedlings from the three quadrats sampled in each plot for our response variable “total seedlings” and fixed effects were source, season and an interaction between source and season, with block included as a random effect. We used R (version 4.0.0) for all statistical analyses (R Core Team 2020).

RESULTS AND DISCUSSION

Our analysis was limited by our small sample size and the fact that only two plots (one local and one commercial) in the spring treatments had any germination of sagebrush. We did, however, find statistically significant evidence that the fall treatment had a greater average number of plants established compared to the spring treatment ($p = 0.0002$, Table A.1). Our findings support existing literature that spring seedings of sagebrush do not result in successful establishment and the appropriate time to seed sagebrush is in the fall (Meyer 2008; Shaw et al. 2005). By seeding later in the fall season (December) we may have overcome some of the concerns that are associated with fall seedings such as germinating too early and being killed off during the first winter.

Our statistical model produced weak evidence of a positive effect on establishment rates by using local seed over commercial seed ($p = 0.046$, Table A.1). There was more variability in local seed establishment rates than in commercial seed establishment rates, and although the median was the same between the two treatments, the means differed with an average of 4.6 seedlings established per local seed plot and an average of 2.6 seedlings established per commercial plot (Fig. A.1). While our results showed some evidence to support that local seed may yield higher establishment rates than commercial seed, we do not have enough data in this study to be conclusive. The average purity rate for commercial big sagebrush is 10-20% (Meyer & Monsen 1992; Meyer 1992). Our local seed had an extremely low seed purity rate (1.3%) relative to the commercial (13.77%) yet still yielded a higher average of sagebrush seedling established per plot. More research with a larger number of replicates is needed in order to determine whether local seed has a significant advantage over commercial seed for mountain big sagebrush. Only four sagebrush individuals were recorded (all in one plot) across all control plots.

TABLES AND FIGURES

Table A.1. Analysis of variance (Type III Wald Chi-square tests) examining the effect of source and season on mountain big sagebrush establishment

Analysis of Variance Table (DF = 1)		
	Chi Sq	P-value
Intercept	0.001	0.97
Source	3.9	0.046
Season	14.2	0.0001
Source * Season	1.3	0.26

Fox Hills Ranch Project Area

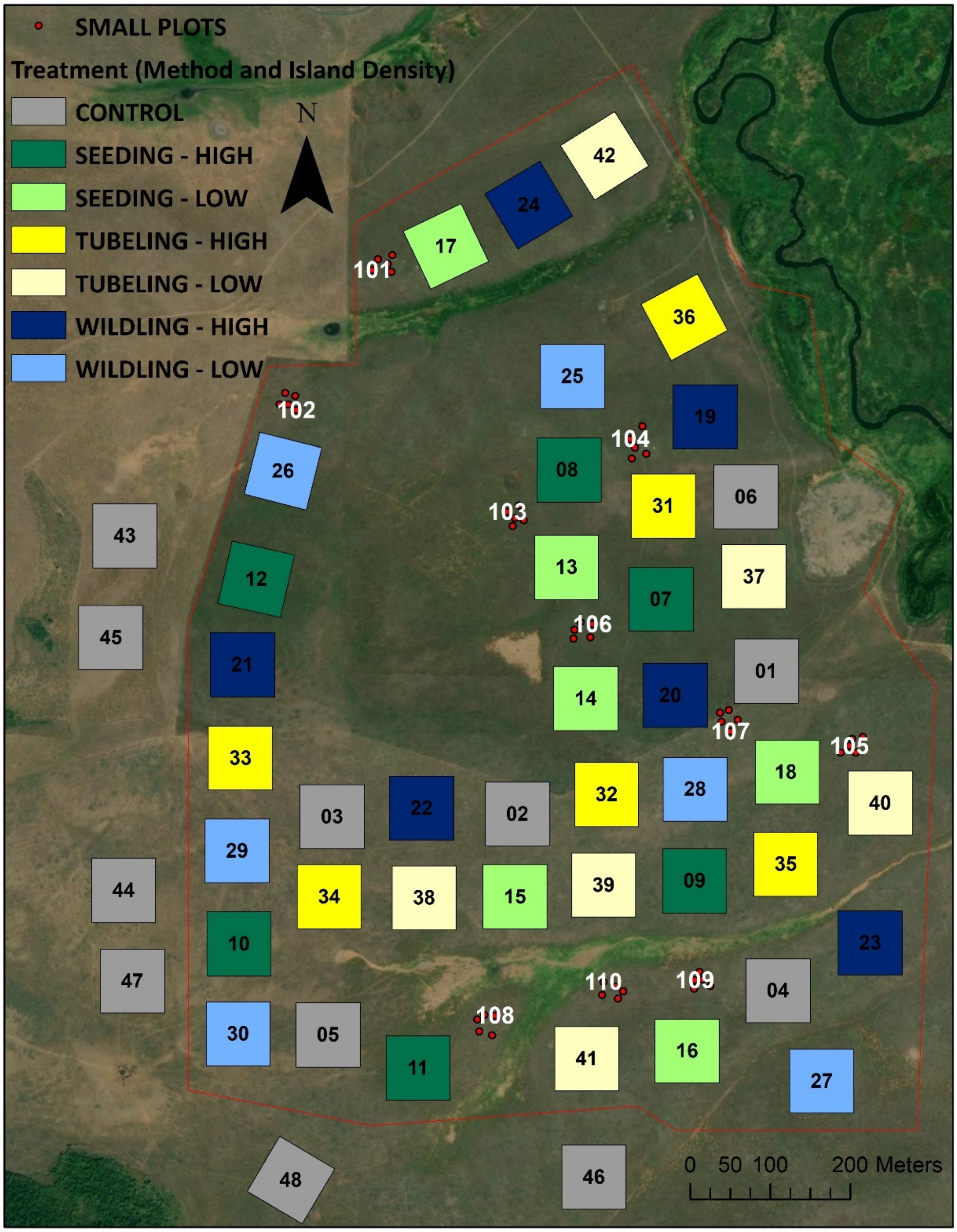


Figure A.1. Research plot layout, including small plots, within project area at Fox Hills Ranch in Southeastern Idaho. Colored boxes (1-46) are plots involved in larger, long-term sagebrush research study. The red points represent the five 3 m x 3 m plots within each block (labelled in white) dispersed across the project area.

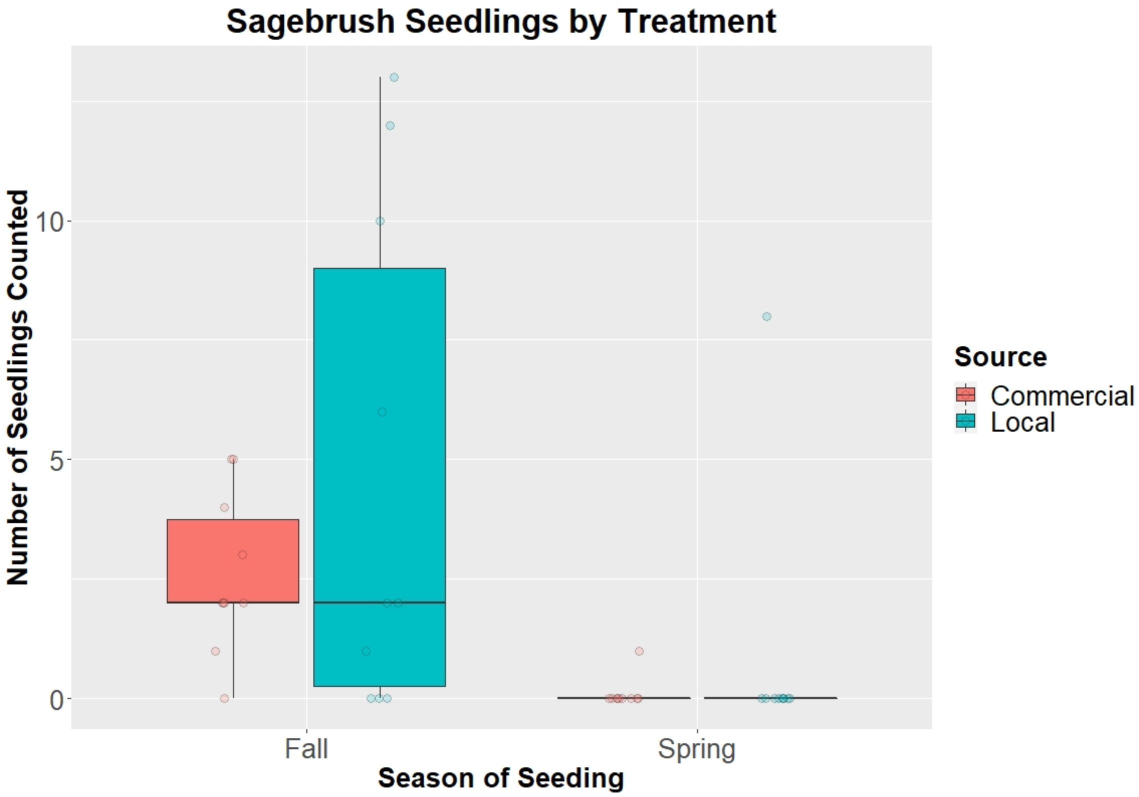


Figure A.2. Seedling counts from the sum of three 0.25 m^2 quadrats in each treatment plot examining effects of source (local vs. commercial) and season of seeding (Fall vs. spring). Each box represents the interquartile range between the 25th percentile and 75th percentile for number of seedlings counted. The bold line in the middle of the box represents the median. The whiskers extend in both directions to the minimum and maximum number of seedlings counted per