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ABSTRACT

Crested wheatgrass [*Agropyron cristatum* (L.) Gaertn., *A. desertorum* (Fisch. ex Link) Schult., and related taxa] often exists in near monoculture stands in the northern Great Plains. Introducing locally adapted yellow-flowered alfalfa [*Medicago sativa* L. subsp. *falcata* (L.) Arcang.] would complement crested wheatgrass. Our objective was to evaluate effects of seeding date, clethodim {(*E*) -2-[1-[[(3-chloro-2-propenyl)oxy]imino]propyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one} sod suppression, and seeding rate on initial establishment and stand persistence of Falcata, a predominantly yellow-flowered alfalfa, no-till interseeded into crested wheatgrass. Research was initiated in August 2008 at Newcastle, WY; Hettinger, ND; Fruitdale, SD; and Buffalo, SD. Effects of treatment factors on plant frequency during initial establishment were influenced by site environments. Late summer and spring were suitable seeding dates. Clethodim sod suppression increased seedling frequency in most cases. Seedling frequency increased as seeding rate increased from 0.56 to 7.84 kg pure live seed (PLS) ha^{-1}. Specific seeding dates, clethodim sod suppression, and high seeding rates did not greatly improve initial establishment when site environments were poor. Residual effects of seeding date and sod suppression post establishment were not significant at most locations, but seeding rate effects were evident. Initial establishment and persistence of Falcata alfalfa was successful at Newcastle, indicating that interseeding in late summer or spring using low seeding rates (≤3.36 kg PLS ha^{-1}) without clethodim can be effective. Assessing grass canopy cover, soil texture, and management (e.g., haying) is necessary to determine the suitability of crested wheatgrass sites for interseeding.

Crested wheatgrass is an introduced cool-season perennial grass from Eurasia and is well-adapted to the northern Great Plains and Intermountain West of the United States. Holechek (1981) estimated that there were about 8.1 million hectares of crested wheatgrass in the United States in the early 1980s. The grass was commonly seeded in large monocultures, but diverse vegetation is more suitable for multiple uses such as livestock grazing, wildlife habitat, and recreation (McKell, 1986). Alfalfa can diversify and increase forage production and quality of crested wheatgrass stands (Kindschy, 1991). Interseeding yellow-flowered alfalfa, which is adapted to semiarid regions, would complement crested wheatgrass and improve the ecological value of stands.

Erratic precipitation and competition from associated vegetation make interseeding alfalfa a risky practice in semiarid regions. Rangeland grasshoppers (Orthoptera: Acrididae) can also contribute to stand failures of interseeded alfalfa (Rumbaugh and Thorn, 1965). Favorable and timely precipitation is one of the most important factors in successful alfalfa stand establishment (Rumbaugh and Thorn, 1965; Schellenberg et al., 1994). Reducing competition from associated vegetation, proper seeding depth, and good seed-to-soil contact are also necessary for alfalfa establishment success (Rohweder and Albrecht, 1995). Seeding rates for interseeding alfalfa in semiarid regions have generally been low, ranging from 0.5 to 2.24 kg PLS ha^{-1} (Derscheid et al., 1965; Rumbaugh et al., 1982; Mortenson et al., 2005).

Optimal seeding dates for interseeding desirable species into established plant stands are similar to seeding dates for conventional full seedings (Vallentine, 1980). Early spring (April) is often recommended as the most favorable time to interseed alfalfa in the northern Great Plains (Twidwell et al., 1993; Manske, 2005). Manske (2005) discouraged interseeding alfalfa in late summer and early autumn because soil moisture from July to October is often inadequate for successful

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Abbreviations: PAR, photosynthetically active radiation; PLS, pure live seed.

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establishment. Dormant seeding in late autumn (November) is preferable to late summer seeding (Derscheid and Johnson, 1970; Manske, 2005). Successful interseeding of alfalfa in late summer (August) has, however, been demonstrated in the region (Rumbaugh and Thorn, 1965).

Historically, interseeding in semiarid regions was a one-pass operation that consisted of creating furrows on wide rows (61–152 cm) followed by seeding into the furrows (Houston and Adams, 1971; Vallentine, 1980; Chisholm et al., 1981; Smith, 1997). Furrow openers simultaneously removed competition from resident vegetation and prepared a seedbed. Furrows made on the contour would catch and hold moisture for seedlings (Vallentine, 1980; Chisholm et al., 1981). In more humid regions, herbicides such as glyphosate [*N*-(phosphonomethyl) glycine] and paraquat (1,1′-dimethyl-4,4′-bipyridinium dichloride) have been used to reduce competition from resident vegetation (Olsen et al., 1981; Vogel et al., 1983; Laberge et al., 2005). Herbicides made low disturbance no-till interseeding into grass sods more feasible and this practice has been evaluated by Schellenberg and Waddington (1997) in semiarid regions of Canada. Alternatives to herbicides, such as heavy grazing, have also been effective in reducing grass competition (Seguin, 1998; Smart et al., 2005).

Herbicides have been broadcast or band applied when interseeding legumes. Banding the herbicide has been recommended when introducing legumes into desirable grass stands (Hall and Vough, 2007). Band spraying requires less herbicide and carrier (i.e., water) than broadcast spraying because only a portion of an area is treated (Blackmore, 1962). In Saskatchewan, Schellenberg et al. (1994) found that increasing the band width up to 75 cm was beneficial for alfalfa establishment but also increased weed biomass in the seeding year.

Previous interseeding research evaluated establishment in the seeding year but often did not evaluate persistence after establishment. Success or failure in semiarid areas cannot be reliably determined in the first or second year after interseeding (Wickstrom, 1970). Seedlings may initially establish but the stand may not persist with time for various reasons. Beuselinck et al. (1994) noted that plant persistence is critical during establishment, but stand persistence becomes important once seedlings establish.

Researchers (Schellenberg et al., 1994) and producers (Smith, 1997) have interseeded yellow-flowered alfalfa into crested wheatgrass. However, inconsistencies in establishment success and changes in technology (i.e., seeding equipment and herbicides) require reevaluation of techniques used to interseed yellow-flowered alfalfa in semiarid regions. Also, previous studies in semiarid regions have not evaluated seeding rates for interseeding yellow-flowered alfalfa. Our objective was to evaluate effects of late summer and spring seeding dates, clethodim sod suppression, and seeding rate on initial establishment and stand persistence of Falcata, a predominantly yellow-flowered alfalfa, no-till interseeded into crested wheatgrass.

MATERIALS AND METHODS

Study Sites

Research was initiated in August 2008 at four locations in the northern Great Plains: Newcastle, WY; Hettinger, ND; Fruitdale, SD; and Buffalo, SD (Table 1). All locations have a continental, semiarid climate. A majority (about 75%) of the annual precipitation occurs from April through September. Native vegetation is mixed-grass prairie. Native rangeland comprises most of the land area, but some tracts of land are farmed or have been seeded to introduced grasses. The Newcastle site was on the western edge of the Black Hills and ponderosa pine (*Pinus ponderosa* C. Lawson) stands were adjacent to the site.

The primary criterion for site selection was that the dominant vegetation was established crested wheatgrass. Selected sites had crested wheatgrass stands that were older than 20 yr. With the exception of Buffalo, it is known that the sites had been farmed in the past. Open interspaces between crested wheatgrass plants distinguished the Newcastle site from the other locations which had more continuous grass cover. Buffalo was the most botanically diverse site with certain areas containing considerable silver sagebrush (*Artemisia cana* Pursh), buffalograss [*Bouteloua dactyloides* (Nutt.) J.T. Columbus], and blue grama [*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths]. Hettinger had lighter soil and higher grass canopy cover than the other locations (Table 1).

The four locations were historically seasonally grazed and/or hayed depending on management objectives. Sites were not hayed in 2008, but the Buffalo site had been grazed in the spring. Hettinger and Fruitdale had higher crested wheatgrass canopy cover than Newcastle and Buffalo at the time of study initiation in August 2008.

Experimental and Treatment Design

The experiment for this study was replicated across 2 yr and four locations. A split-plot experimental design was used at each location, with whole-plots (12.6 by 15.2 m) arranged as a randomized complete block design. Hettinger, Fruitdale, and Buffalo had five blocks while Newcastle had four. Four whole-plots (two randomly assigned to each year) were contained within each block. Whole-plot treatments were two seeding dates: late summer (late August) or spring (mid-May) seeding. Seeding dates in Year 1 were late summer 2008 and spring 2009; seeding dates in Year 2 were late summer 2009 and spring 2010 (Table 1). Ten subplots (2.5 by 7.6 m) were contained within each whole plot. Sod suppression × seeding rate combinations were randomly assigned to each subplot. Two sod suppression levels were clethodim (band applied) at 1 L ha^{-1} and an untreated control (no herbicide application). Five seeding rates were 0.56, 1.12, 3.36, 5.60, and 7.84 kg PLS ha^{-1}.

Alfalfa Establishment

Inoculated Falcata alfalfa (Wind River Seed, Manderson, WY) was no-till interseeded at each location on each seeding date beginning in August 2008. Falcata originated from the Norman Smith ranch near Lodgepole, SD (Smith, 1997) and had been previously demonstrated to be adapted to regional environmental conditions (Misar et al., 2015). One seed lot, maintained in cold storage (4°C), was used for the entire study. Consistency of seed viability (about 96%) was verified by testing (Association of Official Seed Analysts, 2010) before seeding in spring 2009, late summer 2009, and spring 2010. Alfalfa was seeded with a no-till plot drill with single-disk openers (Model 750, Deere & Company, Moline, IL). Each subplot consisted of two seeded rows. Seed was routed to two of the six openers to achieve a row spacing of 127 cm.

Table 1. Site and experiment information for four study locations in the northern Great Plains for evaluating initial establishment and persistence of yellow-flowered alfalfa interseeded into crested wheatgrass.

Site information	Location							
	Newcastle, WY		Hettinger, ND		Fruitdale, SD		Buffalo, SD	
Geographical coordinates	43°51′ N, 104°12′ W		46°0′ N, 102°38′ W		44°40′ N, 103°41′ W		45°35′ N, 103°32′ W	
Avg. max. temperature in July, °C	30.6		28.3		31.4		29.4	
Avg. min. temperature in January, °C	−11.4		−16.1		−11.9		−14.5	
Avg. annual precipitation, mm	408		394		455		399	
Soil series†	Crownest–Regnaps complex		Stady loam and Manning fine sandy loam		Arvada silt loam‡		Savage silty clay loam	
Soil family§	loamy, mixed, superactive, nonacid, frigid Lithic Ustic Torriorthent and fine-loamy, mixed, superactive, frigid Typic Hapludalf		fine-loamy (Stady) or coarse-loamy (Manning) over sandy or sandy-skeletal, mixed, superactive, frigid Typic Haplustoll		fine, smectitic, mesic Ustertic Natrargids		fine, smectitic, frigid Vertic Arguistoll	
Soil texture (0–7.62-cm depth), %¶								
Sand	27		57		34		31	
Silt	46		26		34		38	
Clay	27		17		32		31	
Soil texture class	Clay loam		Sandy loam		Clay loam		Clay loam	
Soil fertility (0–7.62-cm depth)								
pH	7.3		6.5		7.1		6.3	
Available P, mg kg^{-1}#	6		32		30		10	
Available K, mg kg^{-1}	353		657		659		857	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Seeding date								
Late summer	22 Aug. 2008	21 Aug. 2009	25 Aug. 2008	22 Aug. 2009	22 Aug. 2008	21 Aug. 2009	25 Aug. 2008	21 Aug. 2009
Spring	15 May 2009	18 May 2010	18 May 2009	19 May 2010	15 May 2009	18 May 2010	18 May 2009	19 May 2010
Clethodim application date	20 May 2009	23 May 2010	21 May 2009	26 May 2010	21 May 2009	1 June 2010	22 May 2009	26 May 2010
Crested wheatgrass canopy cover (SE), %††	10 (1.8)	26 (3.0)	57 (5.2)	71 (4.9)	42 (6.7)	22 (3.5)	35 (3.5)	42 (7.2)
Post establishment management (2011–2014)	Mid-summer haying		Spring mowing or spring grazing by sheep		Winter-early spring grazing by sheep; mid-summer haying in 2011 and 2014		Dormant season grazing by cattle to limit residue accumulation	

† Soil Survey Staff (2014a).
‡ Arvada silt loam intergrades with Kyle clay (very-fine, smectitic, mesic Aridic Haplustert) north of the site.
§ Soil Survey Staff (2014b).
¶ Hydrometer method.
# Olsen P soil test.
†† Mean of 14 ocular estimates of canopy cover at each location using a 0.25 m^2 quadrat in August of the establishment year.

Clethodim was applied in late spring (late May/early June) (Table 1) when crested wheatgrass was actively growing. Herbicide was applied several days following spring seeding and most alfalfa seeded the previous summer was growing at this time. However, clethodim is a grass selective herbicide which allows application after alfalfa seeding and emergence. Ammonium sulfate (2.8 kg ha^{-1}) and crop oil concentrate (1% v/v) were tank mixed with clethodim. Herbicide was band applied (band width = 40.6 cm) onto the seeded row using a spray boom with even flat spray tips (TP4003E, TeeJet Technologies, Springfield, IL) mounted on an all-terrain vehicle. Spray carrier solution was applied (183 L ha^{-1}) using a pressure of 138 kPa.

Intentional haying or grazing of the plots to reduce grass canopy cover and biomass before interseeding was not conducted. Sheep had access to the Fruitdale plots during the winter of 2009 and early spring months of 2010 but were not on the site during the summer. Livestock did not have access to the plots during interseeding and initial establishment at Newcastle, Hettinger, and Buffalo.

Data Collection

Initial Establishment

Initial establishment in this study can be defined as the period from seed germination to seedling crown development. Initial establishment data were collected during summer 2009 for Year 1 and summer 2010 for Year 2. Initial establishment was evaluated by determining seedling frequency in early July about 45 wk after late summer seeding and 7 wk after spring seeding. Seedling frequency was determined using a 300-cm-long PVC pipe marked with 20 segments (15 cm segment^{-1}) placed next to the seeded alfalfa rows. Frequency data were collected for the center 3 m of each 7.6 m planted row. Presence or absence of alfalfa seedlings within 40 segments (20 segments row^{-1} for two rows in each subplot) was recorded. This procedure was similar to that described by Gates and Dewald (1998). Seedling frequency was determined as:

$$\text{Seedling frequency (\%)} = (\text{no. of segments containing at least one alfalfa seedling/total no. of segments}) \times 100$$

Table 2. Type III tests of fixed effects for evaluating initial establishment and persistence of yellow-flowered alfalfa interseeded into crested wheatgrass at four study locations in the northern Great Plains.

Fixed effect	*F* value	*P* value
Establishment period (E)†	745.81	<0.001
Location (L)	5.63	ns‡
E × L	220.48	<0.001
Seeding date (D)	5.71	0.023
E × D	8.61	0.004
L × D	1.13	ns
E × L × D	7.44	<0.001
Sod suppression (S)	44.70	<0.001
E × S	8.74	0.003
L × S	17.88	<0.001
E × L × S	1.30	ns
D × S	0.06	ns
E × D × S	7.58	0.006
L × D × S	4.59	0.004
E × L × D × S	0.69	ns
Seeding rate (R)	113.85	<0.001
E × R	10.29	<0.001
L × R	1.75	ns
E × L × R	3.72	<0.001
D × R	0.14	ns
E × D × R	0.94	ns
L × D × R	1.65	ns
E × L × D × R	0.33	ns
S × R	0.37	ns
E × S × R	0.17	ns
L × S × R	1.13	ns
E × L × S × R	0.47	ns
D × S × R	1.71	ns
E × D × S × R	0.43	ns
L × D × S × R	0.84	ns
E × L × D × S × R	1.05	ns

† Initial and post-establishment.

‡ ns, nonsignificant at the 0.05 probability level.

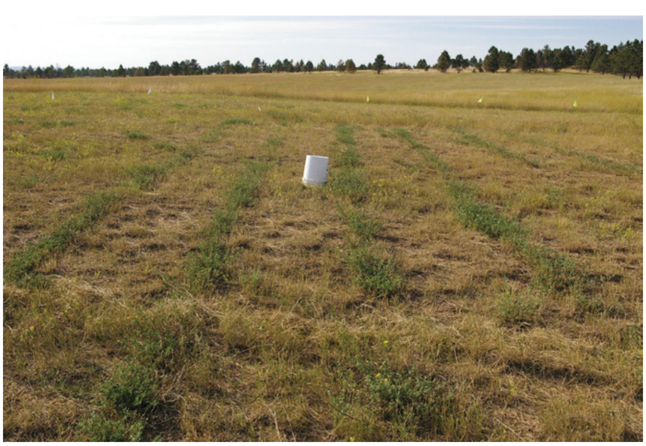

Fig. 1. Established stand of yellow-flowered alfalfa on 30 July 2014 interseeded in spring 2010 (two left rows) and late summer 2008 (two right rows) into crested wheatgrass at Newcastle, WY. Plant frequencies for each row from left to right are 83, 65, 80, and 83%. Photo credit: L. Xu.

Number of plants m^{-1} of row cannot be calculated directly using frequency. Frequency is based only on the presence, not the number, of plants in each segment. Frequency can, however, provide a conservative estimate of plant stand by using calculations similar to Vogel and Masters (2001), who determined plant density (plants m^{-2}) from frequency grid percentages. In our study, a frequency of 100% for a subplot would occur only if there were at least one seedling in every one of the 40 segments evaluated. A frequency of 100% indicates there were at least 40 seedlings in the 6 m of row sampled, which corresponded to at least 6.7 plants m^{-1}. Manske (2005) stated that three to six alfalfa plants m^{-1} of row is a desirable stand if seedlings survive to become mature plants. This corresponded with 50 to 100% frequency in our study when frequency percentages were multiplied by 0.067 to obtain plants m^{-1} of row.

Post-Establishment

Frequency of alfalfa plant occurrence was evaluated in late July 2014 to assess stand persistence of interseeded alfalfa after initial establishment (Fig. 1). Alfalfa stands were 3.25- to 6-yr old at the time of data collection. Stand age was dependent on alfalfa interseeding date and when establishment occurred, particularly for late summer seeded alfalfa. Frequency was evaluated using the same procedure as during initial establishment, except observers counted the number of segments that contained established, mature plants (i.e., crowns).

Sections of the plots at Newcastle and Fruitdale had been cut for hay in early July 2014 before sampling. However, residual stubble and regrowth allowed plant frequency data to be collected. Interseeded alfalfa, which had not been hayed at each location, was in the early to late seed pod morphological stages of development (Kalu and Fick, 1981).

Statistical Analysis

One combined analysis of multiple experiments was conducted after merging datasets from the initial and post establishment periods. Analysis was conducted using PROC GLIMMIX in SAS (SAS Institute, 2012) because frequency data are known to have a binomial distribution (Stroup, 2015). The link function for binomial proportions is the logit (Stroup, 2015). Establishment period, location, seeding date, sod suppression, seeding rate, and their interactions were fixed effects (Table 2). Random effects were year × location, block nested within each year × location combination, the whole-plot error effect (date × block × year × location), the split-plot error effect (suppression × rate × date × block × year × location), and unit level effect (establishment period × suppression × rate × date × block × year × location).

Our analysis focused on three-way interactions to evaluate simple effects of treatment (seeding date, sod suppression, and seeding rate) at each establishment period × location level. In addition, evaluating simple effects of establishment period at each location × treatment level were of interest. Least squares means and standard errors of the logit were estimated using the LSMEANS statement and converted to probabilities using the inverse link. The SLICEDIFF option was used to conduct simple effect comparisons of means. Means were considered different at $P < 0.05$.

Table 3. Growing season (April-September) precipitation at four study locations in the northern Great Plains for evaluating initial establishment and persistence of yellow-flowered alfalfa interseeded into crested wheatgrass. The 30-yr average (1971–2000) is provided.

Year	Location			
	Newcastle, WY	Hettinger, ND	Fruitdale, SD	Buffalo, SD
	% of 30-yr avg.			
Initial establishment				
2008				
Apr.-May	129	115	167	148
June-July	105	105	142	98
Aug.-Sept.†	78	74	117	82
2009				
Apr.-May‡	92	52	62	55
June-July	122	116	69	85
Aug.-Sept.§	80	136	169	61
2010				
Apr.-May¶	132	138	150	117
June-July	108	128	68	108
Aug.-Sept.	13	181	123	248
Post-establishment#				
2011	119	116	94	132
2012	48	113	61	89
2013	147	157	102	120
2014	83	126	74	166
	mm			
30-yr avg.				
Apr.-May	105	105	126	113
June-July	113	130	131	130
Aug.-Sept.	79	73	68	62
Total (Apr.-Sept.)	297	308	325	305

† Year 1 late summer seeding in late Aug. 2008.
‡ Year 1 spring seeding in mid-May 2009.
§ Year 2 late summer seeding in late Aug. 2009.
¶ Year 2 spring seeding in mid-May 2010.
# Apr.-Sept. total precipitation.

Orthogonal polynomial contrasts were used to determine the relationship (i.e., linear, quadratic, etc.) between frequency and seeding rate at each establishment period × location level. Since seeding rate levels were unequally spaced, PROC IML in SAS was used to generate coefficients. Polynomial responses were considered significant at $P < 0.05$.

RESULTS AND DISCUSSION

Precipitation

Initial Establishment

Precipitation (Table 3) influenced seeding date, sod suppression, and seeding rate treatment effects on seedling frequency during initial establishment. Favorable growing season precipitation was beneficial for establishing alfalfa seedlings. In 2009, all locations were drier than average in April and May. Dry conditions persisted into June and July at Fruitdale and Buffalo, but rainfall at Newcastle and Hettinger was above average. Precipitation in 2010 tended to be above average at all locations, particularly in April and May. However, rainfall at Fruitdale was only 68% of average in June and July.

Post-Establishment

Post-establishment growing season precipitation in 2011 and 2013 was near or above average at all locations (Table 3). An exception was 2012, a major drought year in most of the United States. Rainfall at Newcastle was only 48% of average in 2012. Hettinger was less affected by this drought than the other three locations. Growing season precipitation in 2014 was more favorable at Buffalo and Hettinger than at Newcastle and Fruitdale.

Seeding Date

Initial Establishment

Seedling frequency results (Table 4) of initial stands indicated that late summer and spring were suitable seeding dates. Seedling frequency between late summer and spring seeding dates did not differ ($P \geq 0.05$) at each location except Fruitdale. Seedling frequency at Fruitdale for late summer seeded alfalfa was higher ($P < 0.05$) than spring seeded alfalfa. However, the stands were very poor regardless of seeding date. An advantage to interseeding in late summer at this location is negligible from a practical perspective.

Late summer seeded alfalfa will emerge the following spring if dry conditions during autumn limit germination. We observed this at Buffalo and Hettinger and it has been noted by others (Rumbaugh and Thorn, 1965). Alfalfa seeded in late summer may also emerge and successfully establish during autumn if growing conditions are ideal. However,

Table 4. Effect of seeding date on frequency (%) of yellow-flowered alfalfa interseeded into crested wheatgrass at four study locations in the northern Great Plains. Seeding date means were averaged across sod suppression and seeding rate treatment levels.

Establishment period	Seeding date	
	Late summer†	Spring‡
	% (SE)	
	Newcastle	
Initial§	72 (13.0)	54 (16.0)a¶
Post#	69 (14.0)A††	36 (15.0)bB
	Hettinger	
Initial	87 (7.3)a	90 (5.7)a
Post	16 (8.5)b	10 (5.6)b
	Fruitdale	
Initial	8 (4.9)A	3 (2.1)bB
Post	7 (4.1)	6 (3.4)a
	Buffalo	
Initial	54 (15.7)a	60 (15.1)a
Post	8 (4.6)b	5 (2.7)b

† Late Aug.

‡ Mid-May.

§ Frequency assessed in early July 2009 and 2010.

¶ Column means within study locations followed by different lowercase letters are statistically different ($P < 0.05$).

Frequency assessed in late July 2014.

†† Row means followed by different uppercase letters are statistically different ($P < 0.05$).

this occurrence only happened at Newcastle in September 2008 and may be uncommon in northern, semiarid regions. Adequate rainfall and establishment time before a killing frost are necessary. Failure of seedling alfalfa to adequately establish before a killing frost (–2.22°C for > 4 h) could result in poor stands (Cosgrove and Collins, 2003). An advantage of alfalfa establishment during autumn is that grass growth and competition is lower in autumn compared to spring (Seguin, 1998).

Observations in July revealed that late summer seeded alfalfa seedlings were more vigorous and developed than spring seeded alfalfa seedlings. Alfalfa seeded the previous summer was growing in the early spring before alfalfa was spring seeded in mid-May. Growing conditions become less favorable for establishment when alfalfa is interseeded after early May. Late spring seedings (5 May–5 June) are not recommended for western South Dakota (Twidwell et al., 1993). At Fruitdale in 2010, good stands from the mid-May 2010 seeding were observed in early June. However, moisture conditions became drier (Table 3) and seedlings were consumed by grasshoppers. By early July, seedling frequencies were low. In northern states, grasshopper eggs begin to hatch in late May, but forage losses are low until mid-summer when forage destruction increases (Hewitt and Onsager, 1983). Earlier spring planting may have allowed establishment before grasshoppers became a problem. In addition, grass competition is lower in early spring compared to late spring. Klebesadel and Smith (1959) found that light penetrating through a companion crop canopy declined as the crop grew taller and advanced in maturity. Light penetration declined most rapidly during culm elongation (Klebesadel and Smith, 1959). Critical establishment time may be lost if interseeding is delayed into mid-May.

Table 5. Effect of sod suppression on frequency (%) of yellow-flowered alfalfa interseeded into crested wheatgrass at four study locations in the northern Great Plains. Sod suppression means were averaged across seeding date and seeding rate treatment levels.

Establishment period	Sod suppression	
	Clethodim†	Control‡
	% (SE)	
	Newcastle	
Initial§	68 (13.4)aA¶#	58 (15.0)aB
Post††	57 (15.1)b	49 (15.3)b
	Hettinger	
Initial	94 (3.4)aA	79 (10.1)aB
Post	20 (9.6)bA	8 (4.4)bB
	Fruitdale	
Initial	6 (3.2)	5 (3.0)
Post	6 (3.2)	7 (4.0)
	Buffalo	
Initial	65 (14.0)aA	49 (15.1)aB
Post	6 (3.2)b	6 (3.6)b

† Clethodim herbicide applied in late May 2009 and late May/early June 2010 at a rate of 1 L ha^{-1} in a 40.6-cm-wide band centered on the seeded row.

‡ Control had no herbicide application.

§ Frequency assessed in early July 2009 and 2010.

¶ Column means within study locations followed by different lowercase letters are statistically different ($P < 0.05$).

Row means followed by different uppercase letters are statistically different ($P < 0.05$).

†† Frequency assessed in late July 2014.

Post-Establishment

No difference ($P \geq 0.05$) in plant frequency existed between late summer and spring seeding dates in July 2014 at Hettinger, Fruitdale, and Buffalo (Table 4). However, frequency of late summer seeded alfalfa was higher ($P < 0.05$) than spring seeded alfalfa at Newcastle (Table 4). Comparing initial and post-establishment frequency at Newcastle revealed a difference in persistence between the two seeding dates. Late summer seeded alfalfa frequency did not differ ($P \geq 0.05$) between initial and post-establishment, but a difference ($P < 0.05$) did exist for spring seeded alfalfa. Persistence of spring seeded alfalfa was poorer than late summer seeded alfalfa, indicating less favorable conditions for initial establishment of spring seeded alfalfa at this location.

Post-establishment alfalfa frequency at Hettinger and Buffalo was less ($P < 0.05$) than initial establishment frequency for both late summer and spring seeding dates (Table 4). At Fruitdale, no difference ($P \geq 0.05$) existed between initial and post-establishment frequency of late summer seeded alfalfa, but a difference ($P < 0.05$) existed for spring seeded alfalfa. Low post-establishment frequencies at Hettinger, Fruitdale, and Buffalo can be attributed to high plant mortality. Severe stand losses at Fruitdale, however, occurred earlier than at Hettinger and Buffalo.

Sod Suppression

Initial Establishment

Band application of clethodim herbicide resulted in higher ($P < 0.05$) seedling frequency than the control at Newcastle, Hettinger, and Buffalo (Table 5). However, frequency increases from clethodim sod suppression compared to the control tended to be modest (i.e., <20%) at these locations. Benefits from clethodim application were not apparent when growing conditions were poor. Seedling frequencies were low at Fruitdale regardless of clethodim application. No difference ($P \geq 0.05$) in frequency existed between clethodim sod suppression and the control at Fruitdale (Table 5).

Stand, growing conditions, and management (e.g., grazing or no grazing) affected crested wheatgrass canopy cover (Table 1) at each location in both years. Crested wheatgrass canopy cover is negatively correlated ($r = -0.98$) with below canopy photosynthetically active radiation (PAR) (Misar, 2011). Sites with low grass canopy cover (e.g., Newcastle) could be expected to be less competitive with alfalfa seedlings during initial establishment. Clethodim application may be more beneficial at sites (e.g., Hettinger) with high grass canopy cover (≥35%), favorable growing conditions, and late spring interseeded alfalfa. Groya and Sheaffer (1981) noted that high moisture levels increase grass growth, which increases shading of alfalfa seedlings. Companion crops that cause early and extended competition for light are also very competitive for soil moisture (Klebesadel and Smith, 1959). Alfalfa seedlings at Hettinger were observed to be more vigorous and developed if crested wheatgrass was suppressed using clethodim. Below canopy PAR in the establishment year is significantly increased by suppressing crested wheatgrass with clethodim herbicide (Misar, 2011).

Clethodim applied at 1 L ha^{-1} did not kill crested wheatgrass. Under dry conditions (Fruitdale and Buffalo), grass was suppressed and went dormant. Under favorable moisture conditions (Newcastle and Hettinger), crested wheatgrass was suppressed but began to recover later in the establishment year. In either case, crested wheatgrass recovered the following growing season if it had not been grazed but was thinner in former spray bands than adjacent areas.

Post-Establishment

Residual effects of sod suppression were apparent in July 2014 at Hettinger (Table 5). Stands treated with clethodim during establishment had higher ($P < 0.05$) frequency than the control. No difference ($P \geq 0.05$) in frequency between clethodim sod suppression and the control were apparent at Newcastle, Fruitdale, and Buffalo (Table 5). With the exception of Fruitdale, post-establishment frequency at the other three locations was lower ($P < 0.05$) than initial establishment for both sod suppression treatment levels. However, mean frequency only declined about 10% at Newcastle.

Clethodim suppressed crested wheatgrass in the year of application, but grass between spray bands continued to grow and mature. Spray bands in 2009 were present the following spring as strips of green grass in a matrix of taller, standing residue. Selective grazing of crested wheatgrass in spray bands occurred in April 2010 at Fruitdale. Yearling sheep grazed bands more severely than adjacent areas with old residue. If alfalfa had initially established in these bands, it most likely would have been severely grazed. Effects of selective grazing remained once grazing pressure was removed and grass recovery began. In August 2010, curlycup gumweed [*Grindelia squarrosa* (Pursh) Dunal] was growing in the former spray bands, indicating that grazing had weakened the grass further.

Advantages to using clethodim were not realized at most of the locations in this study. Costs to apply herbicide, high risk of poor initial establishment, and poor stand persistence make clethodim sod suppression for interseeding questionable in semiarid regions. Suppressive effects of clethodim on grass do not carry over into the following growing season, a critical time when alfalfa plants are still not fully established. Band applying herbicide over the seeded row after interseeding is not a feasible practice for producers unless their equipment has Real Time Kinematic (RTK) guidance technology (D.L. Beck, personal communication, 2010). This technology would allow herbicide application equipment to accurately follow the same path as the seeder.

Seeding Rate

Initial Establishment

Seedling frequency responses to seeding rate were evident across a range of environmental conditions during initial establishment. Increasing seeding rate resulted in an increase ($P < 0.05$) in seedling frequency at all locations (Table 6). Seedling frequency could often be ranked according to seeding rate. Seedling frequencies were <10% for all seeding rates at Fruitdale (Table 6). Low seedling frequencies at high seeding rates are evidence of poor emergence and/or high seedling mortality. However, seedling frequency responses to seeding rate existed regardless of whether stands were good or poor. Nelson et al. (1998) reported that initial plant stand is related to seeding rate when emergence and seedling survival is below 100% of the total viable seed planted.

Below average and infrequent early growing season precipitation can delay germination and emergence of interseeded alfalfa. In 2009, alfalfa interseeded in May was still emerging at Buffalo in July and Fruitdale in August. Emergence coincided with heavy rainfall a few days before observing the alfalfa, but conditions were dry again after these rains, resulting in seedling mortality. However, other factors contributed to poor establishment. Fruitdale and Buffalo had heavier soils (i.e., higher clay percentage) than Newcastle and Hettinger (Table 1). Heavy soils have slow infiltration rates and are less favorable for plants than lighter soils in low rainfall areas (Holechek et al., 2004). In addition, heavy soils that are puddled and compacted by livestock can be unfavorable for plant establishment and growth (Tiedemann and Lopez, 2004).

Good emergence at high seeding rates (5.60 and 7.84 kg PLS ha^{-1}) initially resulted in thick stands when alfalfa was interseeded in wide rows. Excessive seed may have been planted at high seeding rates, but most seedlings will not establish and become mature plants. Factors including competition and moisture stress will contribute to alfalfa mortality and stand thinning with time (Nelson et al., 1998).

Post-Establishment

Significant ($P < 0.05$) polynomial responses to seeding rate existed in July 2014 for all locations (Table 6). Rankings in plant frequency according to seeding rate were still present. Newcastle and Fruitdale had quadratic response curves for both initial and post-establishment periods (Table 6). In addition, frequency did not differ ($P \geq 0.05$) between initial and post establishment at each seeding rate level (except 7.84 kg PLS ha^{-1} rate level at Newcastle) (Table 6). These

Table 6. Effect of seeding rate on frequency (%) of yellow-flowered alfalfa interseeded into crested wheatgrass at four study locations in the northern Great Plains. Seeding rate means were averaged across seeding date and sod suppression treatment levels.

	Seeding rate, kg PLS† ha^{-1}						
Establishment period	0.56	1.12	3.36	5.60	7.84	Response curve	*P* value
	% (SE)						
			Newcastle				
Initial‡	34 (14.3)	49 (15.9)	68 (13.8)	76 (11.6)	82 (9.6)a§	quadratic	*
Post¶	29 (13.1)	42 (15.5)	57 (15.6)	66 (14.3)	70 (13.4)b	quadratic	*
			Hettinger				
Initial	49 (15.5)a	75 (11.7)a	92 (4.4)a	95 (3.0)a	98 (1.5)a	cubic	**
Post	10 (5.5)b	12 (6.5)b	12 (6.4)b	12 (6.7)b	19 (9.6)b	linear	**
			Fruitdale				
Initial	2 (1.3)	3 (2.1)	8 (4.9)	9 (5.1)	8 (4.8)	quadratic	***
Post	3 (1.8)	4 (2.3)	9 (5.4)	9 (5.1)	10 (5.8)	quadratic	*
			Buffalo				
Initial	19 (10.0)a	42 (15.1)a	67 (13.8)a	73 (12.4)a	83 (8.9)a	cubic	**
Post	2 (1.3)b	4 (2.6)b	5 (3.1)b	9 (5.4)b	16 (8.2)b	linear	***

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† PLS, pure live seed.

‡ Frequency assessed in early July 2009 and 2010.

§ Column means within study locations followed by different letters are statistically different ($P < 0.05$).

¶ Frequency assessed in late July 2014.

results indicate good stand persistence at both locations, even though initial establishment was poor at Fruitdale.

Hettinger and Buffalo had cubic responses to seeding rate during initial establishment but linear responses to seeding rate post-establishment (Table 6). Post-establishment frequency was also lower ($P < 0.05$) than initial establishment frequency at each seeding rate level (Table 6). Plant mortality at these locations either occurred during initial establishment or post-establishment. Initial alfalfa establishment at Buffalo was relatively poor in 2009 and 2010. However, initial establishment at Hettinger was fairly good in those years. The post-establishment response curve to seeding rate was significant ($P < 0.05$) at Hettinger, but plant frequencies appear to be equalizing as the stand thins. Low plant frequencies that are similar across a range of low to high seeding rates is an indication of poor stand persistence.

Intraspecific competition in the first 3 yr after seeding results in rapid thinning of pure alfalfa stands (Beuselinck et al., 1994). However, competition is highly interspecific in interseeded stands. Interseeded alfalfa at Newcastle had better stand persistence than Hettinger because the site had less crested wheatgrass canopy cover and was hayed in mid-summer. Midsummer haying benefits alfalfa because grass competition is reduced and the alfalfa will regrow if soil moisture is adequate (Fig. 1). Cool-season grasses become dormant or produce limited regrowth after mid-summer haying.

Despite poor establishment at Fruitdale and Buffalo, a few alfalfa plants established and were persisting in July 2014. Some seeds were probably planted into favorable microsites such as cattle dung patches and the plants survived despite poor establishment conditions. Other plants may have originated from hard seed, which comprised about 20% of the total viable seed planted. Hard seed is beneficial when unfavorable conditions limit initial establishment and would allow seedlings to establish at a later time (Wickstrom, 1970). The high risk of interseeding in the northern Great Plains suggests that hard seed is beneficial in this region.

High seeding rates are expensive and did not improve initial stands of most interseedings in this study. Low seeding rates (1.12 kg PLS ha^{-1}) may be adequate if seed placement is precise and environmental conditions are favorable (Derscheid et al., 1965). Our research suggests that seeding rates greater than 3.36 kg PLS ha^{-1} may not be necessary for interseeding Falcata alfalfa into crested wheatgrass.

Other Management Considerations

Alfalfa Cultivar or Strain

The current study evaluated various interseeding treatments using Falcata because this alfalfa is adapted to the region and seed was available. Other cultivars or strains of alfalfa differing in genetic background and intended use could be interseeded using these treatments. However, whether other alfalfas would establish and persist similarly to Falcata is unknown. A previous study (Berdahl et al., 1989) demonstrated that in the northern Great Plains, *falcata*-based alfalfas are more suitable for interseeding than *sativa*-based alfalfas. In Berdahl et al. (1989), initial establishment and stands of alfalfa were similar regardless of cultivar or strain. However, persistence of hay-type *sativa* entries was poorer with time than *falcata*-based entries. Adapted *falcata*-based strains are more suitable for interseeding in this region because post-establishment stand persistence is better than other alfalfas.

Environmental conditions have a greater influence on initial establishment success than management factors (including the alfalfa cultivar or strain interseeded). Interseeding Falcata may not necessarily improve initial establishment success when establishment conditions are poor. Young seedlings are at risk of high mortality and initial establishment can be unsuccessful regardless of the cultivar or strain interseeded. Using 3-wk-old seedlings grown in a controlled growth chamber, Kang et al.

(2011) found that cultivar Wisfal alfalfa (*falcata*-based) had greater drought tolerance than cultivar Chilean alfalfa (*sativa*-based). Despite this finding, differences in drought tolerance may not greatly affect seedling survival in an interseeded field because of overriding environmental factors (e.g., prolonged drought, high temperatures, and interspecific competition). This may likely be the case when seedlings are less than 3-wk old. Once initial establishment is completed, however, Falcata is probably able to tolerate poorer environmental conditions better than less adapted alfalfa material.

Type of Crested Wheatgrass

The type of crested wheatgrass growing at a site and how the stand responds to management (e.g., haying) can affect subsequent establishment and persistence of Falcata. Newcastle had less grass canopy cover than the other locations (Table 1) because open interspaces existed between individual plants that grew in bunches (Fig. 1). The crested wheatgrass at Newcastle was *A. desertorum* (i.e., standard type) whereas *A. cristatum* (i.e., fairway type) was at the other three locations. Fairway types are leafier and shorter in height than standard types, which tend to form large clumps when hayed for many years (Sedivec et al., 2010). Before interseeding, the Newcastle site had been hayed most years but was grazed in dry years (K. Culver, personal communication, 2010).

Soil Fertility

Sites in this study were not fertilized before or during interseeding. According to Gerwing and Gelderman (2005), soil test levels for available P were low at Newcastle, medium at Buffalo, and very high at Hettinger and Fruitdale (Table 1). Available K levels were very high at all four locations (Table 1). Phosphorus is important during establishment, but K becomes more critical for stand persistence after establishment (Hall and Vough, 2007). Successful initial establishment at Newcastle indicates that Falcata can establish on sites with low P levels. However, less competition for limited P from the crested wheatgrass at this site was most likely beneficial for establishing alfalfa.

In semiarid regions, nutrient availability is of secondary importance to soil water availability because water is usually limiting (Ries, 1982). Availability of PAR may also be considered more important for interseeded alfalfa than nutrient availability, particularly if the crested wheatgrass stand is highly competitive during and after initial establishment. The Hettinger site had sandy loam soil and high fertility which were conducive for initial establishment. However, the grass stand at this site appears to have been too competitive for Falcata to persist after initial establishment, regardless of whether clethodim was applied or not (Table 5).

CONCLUSIONS

Interseeding Falcata is only successful if an adequate stand initially establishes and then persists for a long period of time. All treatment factors evaluated in this study were effective for initially establishing Falcata but only at specific locations because site environments influenced treatment effects. Results at Newcastle confirm that late summer or spring seeding dates using low seeding rates ($\leq$3.36 kg PLS ha^{-1}) without clethodim sod suppression can be effective for successfully interseeding Falcata. However, the same seeding dates, sod suppression using clethodim, and high seeding rates did not greatly improve establishment at Fruitdale and Buffalo where environmental conditions were poorer. Adequate stands initially established at Hettinger, but treatment factors had little effect on poor stand persistence after initial establishment. Crested wheatgrass competition and post-establishment management (e.g., haying or grazing) appear to have a greater influence on Falcata stand persistence.

Inadequate precipitation, high interspecific competition from crested wheatgrass, grasshoppers, and heavy soils were detrimental to initial establishment. A feasible approach for reducing risk is to interseed suitable sites using techniques that are known to be effective but are low cost. Sites such as Newcastle with low grass canopy cover are more suitable for no-till interseeding Falcata, particularly if sod suppression is not utilized. Sites with high grass canopy cover (e.g., Hettinger) are inherently more risky to interseed and reducing competition is more critical. Clethodim does not reduce competition long enough for this herbicide to be reliably used on these sites. Using strip-tillage that retains some residue on the soil surface or glyphosate sod suppression are alternatives. Further evaluation of techniques such as strip-tillage and management that can improve Falcata establishment success and persistence on highly competitive crested wheatgrass sites is necessary.

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