Dune Habitat Trends of an Endangered Species, *Penstemon haydenii* (Blowout penstemon) in Wyoming

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Abstract

We georectified and analyzed historic aerial imagery and more recent orthoimagery (1946-2012) to determine past trends of 16 dunes currently occupied by *Penstemon haydenii* in Wyoming, measuring total active dune area, downwind active dune area and dune movement over time. Results reveal that active sand dunes persisted continuously over time back to at least 1946. The aerial extent of *P. haydenii* habitat in Wyoming declined about 13.5% in this period, a limited degree of change compared with that in Nebraska Sandhills where there was great habitat loss and disappearance over the same time period, the original basis for listing under the Endangered Species Act. Trends differed significantly between dunes, providing evidence of successional habitat diversity and landscape dynamics in Wyoming. Data are incomplete for comparing habitat trends with population trends but it is hypothesized that stabilization of blowout features are conducive to colonization.

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Introduction

The purpose of this study was to document habitat trends at dunes occupied by *Penstemon haydenii* (Blowout penstemon) in Wyoming, as determined by analyzing historical imagery of the dunes over time. This is needed to determine whether *P. haydenii* habitats in Nebraska and Wyoming are analogous for recovery purposes, to integrate habitat trend information with population trend information, and to inform recovery standards.

Penstemon haydenii was listed as Endangered under the Endangered Species Act (ESA) when the species was only known from Nebraska (USDI Fish and Wildlife Service 1987). Likewise, recovery goals and standards were prepared that addressed its Nebraska status (Fritz et al. 1992), defined in terms of the number of populations that are needed at a given population size threshold of 300 plants over time. Thus, recovering the species by some numeric standards required repeated monitoring at multiple sites.

Penstemon haydenii was discovered in Wyoming in 1996 but not confirmed from the state until 1999 (Fertig 2000). It is the only plant species listed as Endangered under the ESA (USDI Fish and Wildlife Service 2014, Heidel et al. 2008). Systematic surveys for new locations of *P. haydenii* in Wyoming ensued (Fertig 2001, Heidel 2006, 2012) and 12 years of revisits were made to conduct monitoring work at one or more discrete dune areas as a contribution to gauging recovery.

Recently, the *Penstemon haydenii* recovery status was addressed in a 5-year review (USDI Fish & Wildlife Service 2012). The review called for a recovery plan update incorporating new status information, refining recovery criteria and identifying research needs:

> "The revised recovery plan should include objective, measurable criteria which address all listing factors and which, when met, will result in a determination that the species be downlisted and eventually removed from the Federal List of Endangered and Threatened Plants. Recovery criteria should include population growth rates over time and documentation of populations dispersing to unoccupied habitat" (USDI Fish & Wildlife Service 2012).

> "Determine mechanisms of habitat persistence, i.e., how long blowouts persist and the factors causing their healing and mechanisms for migration of plants to new habitat" (USDI Fish & Wildlife Service 2012).

The preceding statements signify recognition that dune trends exert influence over population trends, so that both need to be considered at some level in future *P. haydenii* recovery planning.

Background

Penstemon haydenii is a psammophile that responds positively to the force of wind and to sandblasting by increased plant height, stem diameter and biomass (Stubbendieck et al. 2010). Throughout its range, *P. haydenii* is restricted to active sand dunes centered at blowout features. In Nebraska, *P. haydenii* is found mainly in the sand dune blowout bowls. Despite the high wind turbulence in blowouts, vegetation encroaches in the absence of any natural or man-made disturbances and population numbers decline as habitat suitability and habitat extent decline (Stubbendieck et al. 1989). Designation of *P. haydenii* as Endangered was based in large part on sand dune habitat loss associated with stabilization actions across the Nebraska Sandhills since the 1930's Dust Bowl and accompanying low probabilities of seed dispersal and seedling establishment (USDI Fish and Wildlife Service 1987;

discussed in Sutherland 1988, Hardy et al. 1989, Jobman 1989). By contrast, there is no historic trend data for *P. haydenii* numbers or habitat in Wyoming. To address this need, the Bureau of Land Management (BLM) in Wyoming supported the previously-mentioned surveys in cooperation with Wyoming Natural Diversity Database (WYNDD), in addition to a monitoring study that included census and demographic analysis (Heidel 2007), opportunistic surveys and census work, and this study.

During *Penstemon haydenii* surveys and censuses in Wyoming, all active sand dune surfaces were traversed and many Global Positioning System (GPS) points were collected to record subpopulation extent. The points were converted into shapefiles and projected onto digital orthophotographs. Survey observations and aerial imagery interpretation indicated that Wyoming *P. haydenii* populations are restricted to active sand dunes that have blowout features, generally downwind from blowouts at the rims, downwind slopes, and slip faces that form downwind or laterally where sand intercepted topographic barriers (Heidel 2012). Exceptions to this have been found in extremely low numbers in upwind settings, or as what appeared to be non-surviving numbers within the blowout bowls. The plants around each discrete blowout were treated as discrete subpopulations, and the digitized distribution boundaries of each subpopulation were located downwind from blowout bowls, hereafter referred to as the downwind active dune area. Thus, the downwind active dune areas are downwind portions of active dunes that represent the working hypothesis for delimiting potential habitat, based on virtually all species' mapping to date.

A small demographic study of *Penstemon haydenii* was set up in Wyoming to track all individual plants within three belt transects starting in 2003. Transects were subjectively placed in areas of high *P. haydenii* density, and read for a minimum of four years. None of the three transects had new plants appear within them over the years, and the age of plants in the sample area at the time of plot establishment was unknown, so demographic output was limited to discussing transitions between flowering and vegetative states and size-dependent mortality (Heidel 2007). Incidental to *P. haydenii* demographic and census monitoring, changes to dune morphology were noted.

The overall *Penstemon haydenii* habitat trends in Wyoming were unknown during the limited time it has been known in the state, unlike the overall Nebraska habitat trends. In 2012, it was first hypothesized that there is not vegetation encroachment of *P. haydenii* habitat reducing population numbers in Wyoming as compared with Nebraska (Heidel 2012). Blowout rims occupied by *P. haydenii* that were intact for consecutive years in 1999 through 2005 were observed to "blow out" in 2006, or to breach in increments, accompanied by deposition in both the upwind bowl and the downwind lee slopes where *P. haydenii* plants were buried. Steep sand slip face slumping was observed, burying or eroding out parts of the *P. haydenii* subpopulation and starting new phases of dune migration.

Monitoring of *Penstemon haydenii* has usually been done at the time of flowering when plants are most conspicuous, and as a gauge of reproductive vs. vegetative output. Monitoring conventions used in Nebraska were followed in Wyoming, although it was frequently observed that Wyoming plants were buried to different degrees, and burial obscured stem connectivity. Stem-spacing patterns were well-documented in the demographic monitoring and a spatial delimitation rule was added that all stems farther apart than 15 cm would be counted as separate plants (genets). This rule was examined closer in 2013, when excavations were conducted between 20 paired *P. haydenii* stems at three separate dunes, between pairs of plant stems located 15 cm – 100 cm apart, i.e., a distance at which they would ordinarily be counted separately. The purpose of this small exercise was to determine if *P. haydenii* has vegetative reproduction as necessary information to interpret population census and ensure that census counts did not over-count genetically unique individuals if there was underground vegetative reproduction and connectivity (Tepedino 2012). In excavating sand between 20 pairs of plants, there were no rhizomes connecting the stem pairs, so that all vertical stems represented genets. This supports the convention for delimiting genets.

The 2013 exercise also documented that some above-ground stems of *Penstemon haydenii* showed signs of as many as three prior burials. In a couple instances, excavations encountered completely buried *P. haydenii* stems vertically-oriented over 15 cm below the surface with no above-ground growth and possessing small new shoots that were weeks if not months away from reaching the surface. The underground stems were encountered by chance between the surface pair of stems. This confounds the census conventions and documents the species' ability to survive burial for extended periods. This capacity might explain the sharp rise in population numbers documented in one year of consecutive annual monitoring (2005) but not before or after (2004 or 2006). It is not known whether the underground shoots remain buried all growing season (seasonal dormancy, in the sense of Lesica 1994) or they were only delayed in their emergence. In any case, this phenomenon indicates that Wyoming census results are not over-counts but under-counts, diminishing the value of population census where burial appears to be widespread. The documentation of *Penstemon haydenii* plants surviving complete, prolonged burial adds to the case for analyzing historic dune habitat trends in Wyoming to help interpret population trends in Wyoming.

Results of *Penstemon haydenii* seed ecology studies recently became available (Tilini 2013) documenting that the germination of seeds buried greater than 4 cm was dramatically suppressed, but that these same seeds could be germinated when removed, and treated in post-burial incubation. This simulates natural conditions under shifting sands. Their germination was highest when removed seeds were then dessicated and subject to moist chilling. It was hypothesized that the latter ensures germination during the optimum season in spring (Tilini 2013).

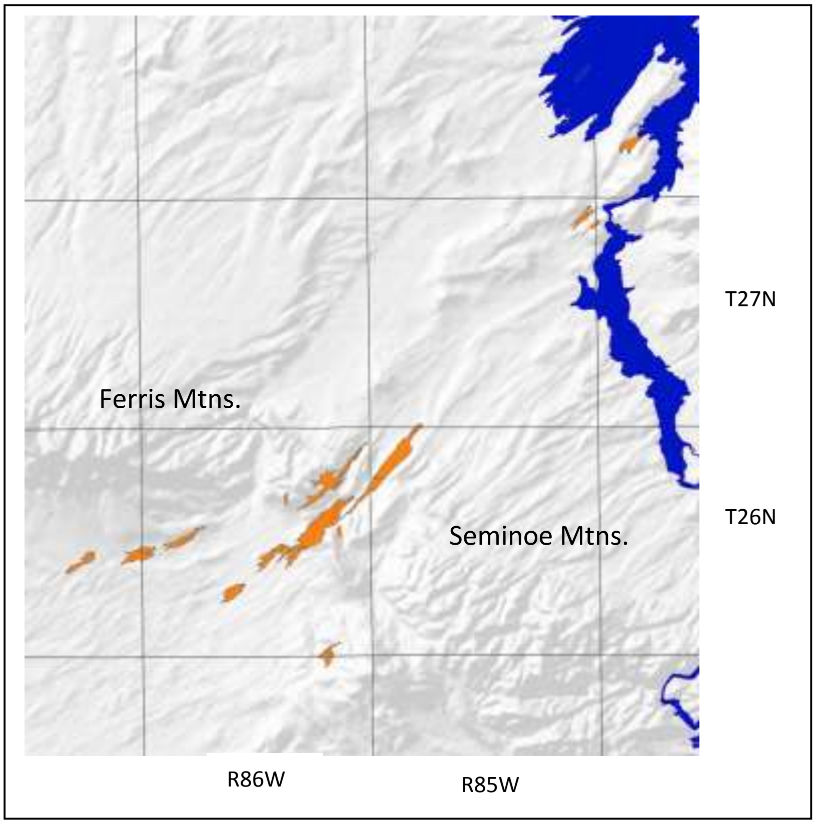
Study Area

In Wyoming, *Penstemon haydenii* is restricted to the Ferris Dune Field, located at the eastern (downwind) end of the Great Divide Basin in the BLM Rawlins Field Office. The presence of the active dunes in the Ferris Dune Field reflects the windy, arid climate and supply of loose sand (Kolm 1982, Gaylord 1984). This is not a formal name, and they lie in the center of a topographically enhanced wind flow that has been referred to as the "Wyoming Wind Corridor" (discussed in Gaylord 1984, from: Kolm and Marrs 1977). The sand dune ages of the Ferris Dune Field, its sand sources, past and present climates including wind flow, and small- and large-scale geomorphic features, were analyzed by Gaylord (Gaylord 1982, Marrs and Gaylord 1982, Gaylord 1984, Gaylord and Dawson 1987).

The Great Divide Basin is fringed by the Ferris and Seminoe Mountains at its eastern end, and these two mountains are separated by a low saddle between them on the Continental Divide. The break in topography acts similar to a wind funnel, and the sand deposits in this area reflect both the confluence and acceleration of airflow though the gap, and episodic hydraulic jumps (Gaylord and Dawson 1987). Dunes upwind of this saddle in the Great Divide Basin have been referred to as the "Main Ferris Dune Field" and those downwind as the "Ferris Dune Field Tail" Gaylord (1984). The most active blowout features in the eastern Main Ferris Dune Field and in the Ferris Dune Field Tail are occupied by *Penstemon haydenii*.

The distribution of *P. haydenii* is mapped as series of 16 discrete dune subpopulations that are provisionally grouped into three populations, recognizing two small populations in isolated southern and northeastern locations and an extensive, central population that straddles the Continental Divide (Figure 1).

Figure 1. *Penstemon haydenii* dunes, Ferris Dune Field, Wyoming[4]



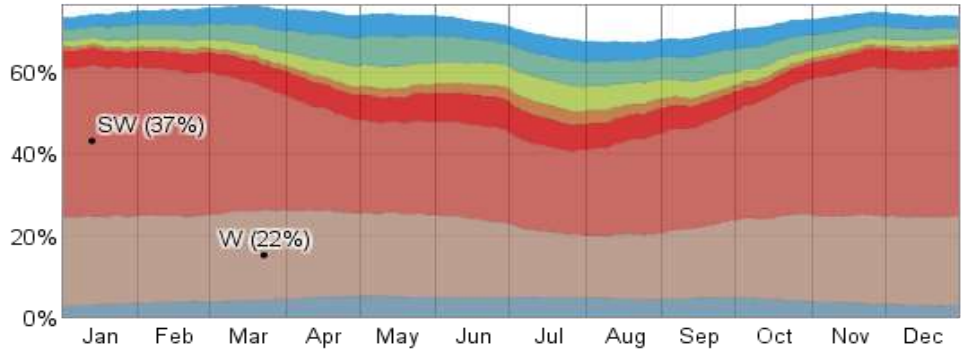
The Ferris Dune Field includes many parabolic sand dunes, a dune type that is typically horseshoe-shaped, with an actively-migrating leading edge at the center and long arms that are pinned down by vegetation and extend upwind on either side wrapping around a blowout bowl (Gaylord 1982, 1984). Parabolic dunes form under unidirectional winds, and the main Ferris dunes are aligned at N 65°-70° while those farther east are at about N 45° orientation (Gaylord 1982, 1984). Their orientation reflects prevailing winds out of the southwest and west throughout the year. The strongest winds occur between October and April when southwest and west winds are especially prevalent (Figure 2). Average yearly wind speeds range from 8.1 to 9.3 m/sec as determined from anemometers mounted within and near the Ferris Dune Field (Gaylord 1984).

Wind speeds of 4.7 m/s mobilize fine-grained quartz sand of 0.18 mm diameter into suspension, whereas wind speeds of 9.0 m/sec mobilize quartz sand of 0.50 mm diameter. (Table 1, in Gaylord 1984). Average grain size of the Main Ferris Sand Dunes was determined as 0.38 (mean), 0.51 mm (mode) and

[4]*Penstemon haydenii* dunes are represented here by their maximum extent of active sand over time (1946-2012). The 16 dunes are discrete throughout this timespan, and exhibit upwind and downwind continuities or discontinuities.

0.23-1.45 mm (minimum-maximum) based on 176 samples (Marrs and Gaylord 1982). In general, grain sizes from upwind sites were larger than downwind sites.

Figure 2. Fraction of time spent with various wind directions – Rawlins, WY
From: WeatherSpark (http://weatherspark.com/averages/31526/Rawlins-Wyoming-United-States)



For sand dunes to remain active, the common wind speed must be strong enough to move the average-sized particles in the sand deposits (Marrs and Kolm 1982). Average rates of Ferris Dune movement were calculated at 8.4 m/year based on distances measured between the leading edges of 35 dunes of the Ferris Dunes Main Field as determined in 1944 and 1975 aerial photographs (Gaylord 1982). The range of migration rates varied from about 3 m/yr – 22 m/yr (From Figure 27 in Gaylord 1984). In addition to suspension, sand moves by saltation, the bouncing of sand grains near the sand surface, and heavier particles move by surface creep, jolted forward when struck by smaller grains (Field et al. 2009). The study area winds also move sand in violent turbulence ("hydraulic jump" of Dawson and Marwitz 1982) and wave-like patterns, exacerbated by topographic relief and the confining influence of surrounding mountainous topography. The turbulence produces airflow recirculation, wind stagnation, and small-scale eddies (Gaylord and Dawson 1987). Finally, sands move on slopes that approach or exceed the angle of repose, under the force of gravity, moving as grains or as slip face slumps. The different dune settings (climbing, falling, and paralleling prevailing winds) and interception by topographically-complex steep or gentle slopes, have different contributions of sand movement forces by winds and gravity. As a result, the dune shapes and sizes of occupied habitat vary greatly.

All of the dunes occupied by *Penstemon haydenii* are parabolic dunes located at topographic barriers, whether on gentle or steep slopes, and whether the dunes climb, fall, or are oriented parallel to the prevailing topography. They are at the least-stabilized end of a gradient described for the Ferris Dune Field from west to east, respectively (Dawson and Marwitz 1982, as discussed by Gaylord 1982). This gradient is described as reflecting the general eastward increase in wind speed across the dunes , decrease in wind carrying capacity as it encounters the Ferris-Seminoe Mountain barrier (Gaylord 1982), the increases in atmospheric instability and wind turbulence with terrain irregularity, and possibly decrease in dune age (Gaylord 1984).

Methods

Aerial imagery was compiled to represent occupied habitat of *Penstemon haydenii* in the corresponding portion of northwestern Carbon County (Heidel 2012). Suitable imagery included 13 aerial photograph sets from three different sources having partial or complete coverage, of which one was culled because coverage was incomplete and the year was consecutive with an earlier or later year having complete coverage. Aerial photographs were scanned at 21 um/pixel with an Epson 10000XL. Five orthoimage sets were available with complete coverage (1994-2012; Table 1). In total, a maximum of 12 different years of imagery were analyzed.

Erdas Imagine 11.0.2 (Intergraph Corp., Englewood, CO) was used to georeference images from 1977 and before. A complete record of georeferencing prior to photointerpretation is presented in Appendix A. Leica Photogrammetry Suite 11.0.2 (Intergraph Corp., Englewood, CO) was used to orthorectify the 1982 imagery using USGS 10-m digital elevation model. Images from 1994-2012 were orthorectified by USGS or USDA following their standard orthoimage production processes (USGS 2014, APFO 2014). All rectification and digitizing was done by S. Cox as having the advanced GIS proficiency and the absence of on-site familiarity that might bias interpretation.

Table 1. Image sets used in analysis of total active dune area and downwind active dune area delineation

Year	Source	Project	Date	Coverage	Image Scale	Frame IDs
1939	BOR	NPIW	22-Apr	Partial	1:20,000	3-49, 3-50
1946	USGS	GS-CM	1-9 Aug	Partial	1:27,000	1-24, 2-14, 3-05, 1-140, 1-141, 1-117
1948†	USGS	GS-IB	10-Sep	Partial	1;24,000	2-40
1949	USGS	GS-JG	4 Oct-2 Nov	Complete	1:33,000	1-40, 2-18, 2-39, 2-41, 2-86
1954	USGS	VV ASM 15 AMS	23-Aug	Complete	1:60,000	1428, 2434, 2435
1975	BLM	RWIR	28-Jun	Complete	1:32,000	7-31-40, 7-32-36, 8-28-50—51, 11-29-41—46
1977	USGS	GS-VEHJ	16-Oct	Complete	1:80,000	5-114, 5-145, 5-155
1982	BLM	WY82AC	7 Jul - 26 Aug	Complete	1:24,000	6-36-6—13, 6-38-1—7, 7-32-35—38, 10-4-2, 12-34-7—10, 12-35-7—14, 13-37-6—11, 13-39-1—4
1994	USGS	NAPP	22-Jul	Complete	1:40,000	Carbon County Mosaic
2001	USDA	NAPP	16-Jul	Complete	1:40,000	Carbon County Mosaic
2006	USDA	NAIP	13-Jul	Complete	1:40,000	Carbon County Mosaic
2009	USDA	NAIP	22 Jul - 11 Aug	Complete	1-m GSD	Carbon County Mosaic
2012	USDA	NAIP	11-Jul	Complete	1-m GSD	Carbon County Mosaic

†Ultimately not used in analysis

The 16 dune blowouts correspond with almost all known 19 *Penstemon haydenii* subpopulations identified in Heidel (2012). The Bear Mountain dune that was mapped as one dune on earliest historical imagery later fragmented into two segments, and has been treated as two subpopulations for monitoring purposes. One of the dune areas west of Junk Hill with two semi-confluent blowout features and subpopulations was mapped in this project as one dune but treated as two subpopulations for monitoring purposes. There is one small dune that is not included because it did not have a blowout rim as used to demarcate occupied habitat for analysis. It is a dune area of less than 1.8 ha (4.5 ac) made up of interrupted occupied habitat. It had 83 plants in 2011 and was the only area excluded in this analysis. For all other areas currently occupied by *P. haydenii*, both the total dune and downwind dune areas were digitized using ArcMap 10.0 (ESRI, Redlands, CA). The boundaries around the contiguous area of active sand were digitized as representing the total dune area. Nested within it, the downwind dune area was digitized as representing a working approximation of potential habitat as botanists have mapped species' distribution to date. Digitizing was done at scales from 1:2,000 – 1:10,000. For each polygon of potential habitat, a point was digitized at the tip of the downwind leading edge of active sand. The 1939 aerial imagery was used to digitize total active dune area at two sites (2 and 3), and was only suitable for digitizing downwind active dune area at one of those sites (# 3). There were other years of imagery in which it was not possible to delineate downwind active dune area at certain dunes, whether because the aerial was too washed out to see a rim, or because the dune area did not have a rim as used to demarcate downwind active dune area. Only Dune 13 had potential habitat delineations for all 12 years, while eleven dunes had potential habitat delineations for at least nine years. The end result was digitization of 318 polygons, for the 16 dunes at up to 12 intervals (176 total active dune areas and 142 downwind active dune areas).

All areas (total dune area and downwind dune area) were digitized and graphed (Appendix B). The distance between successive leading edges was also calculated, and converted to mean annual movement rates to compare dune migration rates with total and downwind dune area trends. To determine trends, all total and downwind dune area values over time were graphed, and the mean, standard deviation and coefficient of variation values for total and downwind dune areas were calculated at a given site. The total and downwind dune area trends were characterized in comparing the 2012 values vs. mean values.

Results

Dune habitat currently occupied by *Penstemon haydenii* is spatially congruent with active dune areas extending back in time over the 66-year time span as represented by available aerial imagery. This indicates that its habitat has persisted. Two of the three largest dunes saw overall increases in downwind active dune area over the period, and the three largest dunes encompass more downwind active dune area than all the rest of the dunes combined (Figure 3). Most small dunes saw decreases in downwind active dune area. Total active dune area declined for most dunes (Figure 4). Total active dune area was 472.6 ha (1167.9 ac) in 2012, a 14.8% decline from the mean total area of 554.6 ha (1370.5 ac). Downwind active dune area was 297.7 ha (735.6 ac) in 2012, a net 13.5% decline from a mean of 344.0 ha (850.1 ac; Table 2).

The leading edges of advancing dunes occupied by *Penstemon haydenii* did not move downwind at constant rates but in fits and spurts, including retreats that signified net contraction of the dune. The highest rate of dune movement was documented for Dune 10, at 1181 m over the 66-year span of aerial imagery, i.e., 17.9 m/yr. Four of the 16 dunes had retreat in leading edges. One of the lowest rates of dune movement was documented for Dune 13, with a cumulative retreat of 599 m, an average retreat of 9 m/yr. The average rate of dune movement among all 16 dunes occupied by *P. haydenii* is 2.8 m/year. The dune with the highest movement rate, Dune 10, is one of the three largest, whereas the other two very large dunes had rates of 9.9 m/year and -4.7 m/yr. This suggests that dune migration trend is not directly coupled with dune area trend, and reinforces the interpretation that the dunes occupied by *P. haydenii* are part of a dynamic dune field system.

Figure 3. Total active dune area in 2012 vs. the multi-year mean (1946-2012)

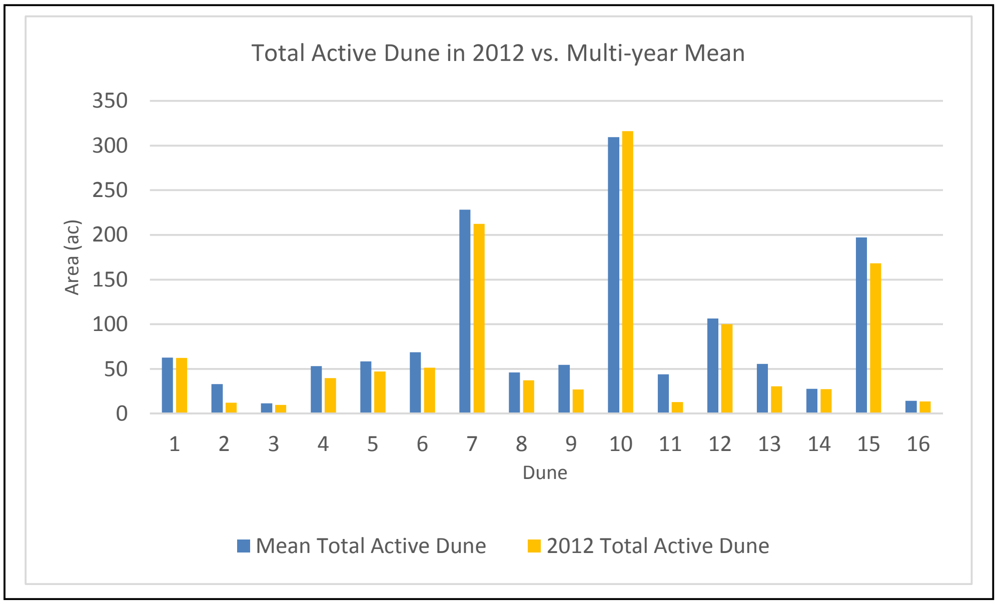
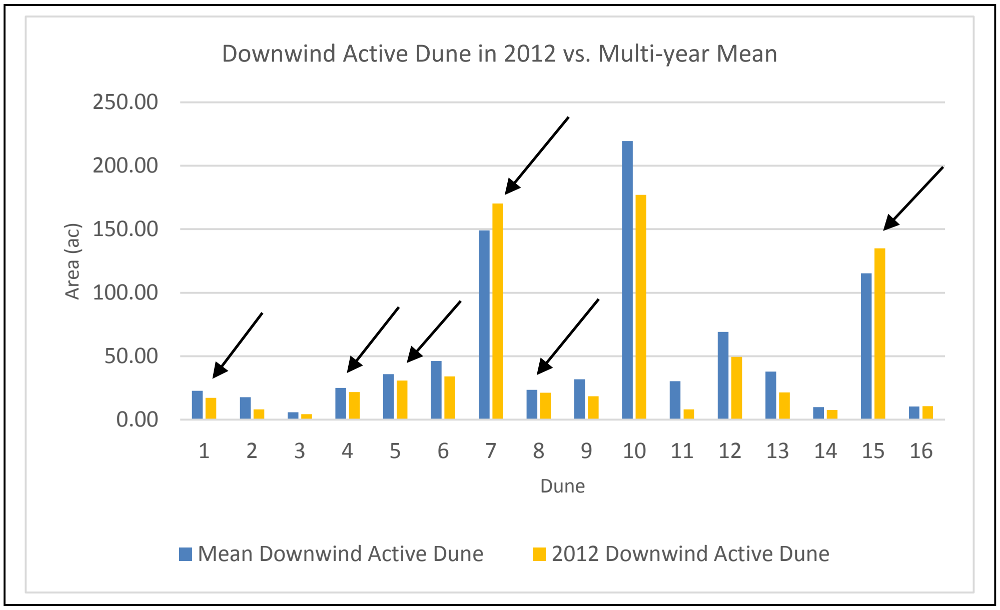


Figure 4. Downwind active dune area in 2012 vs. the multi-year mean (1939-2012)[5]



Six of the 16 dunes occupied by *Penstemon haydenii* have been documented to have over 300 plants in any one or more years of census during the past 12 years as relates to original recovery standards (Figure 4). They include Dunes 1, 4, 5, 7, 8 and 15 as delineated for this study, all of which have a mean downwind active dune area that exceeds 20 ac (8.1 ha).

[5] Arrows point to the downwind active dune area trend bars of those dunes that have ever had 300 or more *Penstemon haydenii* plants documented in census.

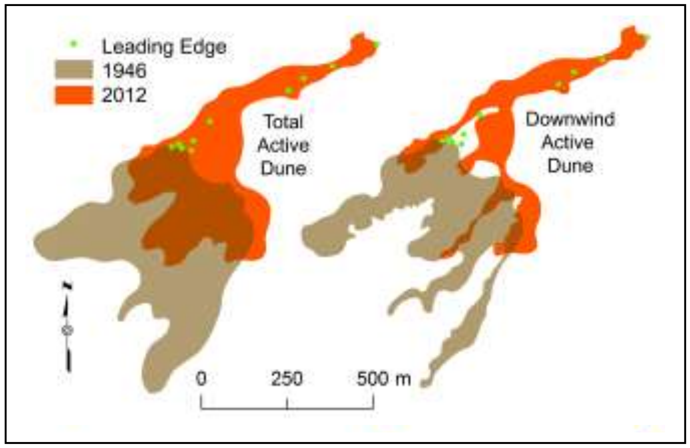
All sand dunes present in early imagery persisted in subsequent years. No dunes appeared for the first time over this time period, although there were many changes to outlines and positioning of existing dunes. There is no evidence that downwind active dune areas or dune migration rates changed in synchrony among dunes. There is at least one dune where a blowout rim formed within a featureless sheet-like area of moving sand in Dune 7. It formed by 1982 and was absent in all prior imagery. If these rims demarcate prime habitat of *Penstemon haydenii* from most or all of unoccupied upwind habitat, as has been hypothesized, then this formation of a blowout feature may signify new or enhanced habitat in Dune 7 that has had among the two largest subpopulations in monitoring over the past decade (Heidel 2012). The formation of a rim ca 1982 may mark a stabilization event, that is, creation of suitable habitat.

Table 2. Dune movement, total dune area, and downwind dune area for 16 dunes, comparing mean values with most recent values (2012)

	Dune Movement		**Total Active Dune Area**					**Downwind Active Dune Area**				
Dune	**Net Leading Edge Movement (m)**	**Mean Net Movement/Year (m)**	**Mean Total Active Dune Area (ac)**	**SD**	**CV**	**2012 Total Active Dune Area (ac)**	**Difference between 2012 and Mean Total Active Dune Area (ac)**	**Mean Downwind Active Dune Area (ac)**	**SD**	**CV**	**2012 Downwind Active Dune Area (ac)**	**Difference between 2012 and Mean Downwind Active Dune Area (ac)**
1	479	7.3	62.7	8.4	0.13	62.30	-0.40	22.7	6.4	0.28	17.30	-5.40
2	-88	1.2	32.9	21.8	0.66	12.10	-20.80	17.8	14.1	0.79	8.00	-9.80
3	64	0.9	11.3	1.3	0.12	9.80	-1.50	5.8	1.3	0.22	4.40	-1.40
4	392	5.9	53.2	12.2	0.23	39.80	-13.40	25	5.1	0.20	21.80	-3.20
5	133	2	58.5	11.1	0.19	47.20	-11.30	35.8	8.7	0.24	30.70	-5.10
6	45	0.7	68.5	12.7	0.19	51.40	-17.10	46.1	12.6	0.27	34.00	-12.10
7	659	9.9	228.2	46.9	0.21	212.20	-16.00	149.2	11.7	0.08	170.40	21.20
8	638	9.7	46.1	21.9	0.48	37.40	-8.70	23.5	7.1	0.30	21.30	-2.20
9	81	1.2	54.4	26.9	0.49	26.90	-27.50	31.7	18	0.57	18.40	-13.30
10	1181	17.9	309.3	57.8	0.19	316.10	6.80	219.5	33.5	0.15	177.00	-42.50
11	-35	-0.5	43.8	31.4	0.72	12.80	-31.00	30.3	21.6	0.71	8.00	-22.30
12	261	4	106.6	13.8	0.13	100.00	-6.60	69.1	13.8	0.20	49.60	-19.50
13	-599	-9.1	55.6	21.1	0.38	30.60	-25.00	38	14.5	0.38	21.50	-16.50
14	6	0.1	27.8	1.2	0.04	27.50	-0.30	9.8	1.1	0.11	7.50	-2.30
15	-525	-4.7	197.2	27.3	0.14	168.20	-29.00	115.4	14.8	0.13	135.00	19.60
16	-2	-0.03	14.4	3.8	0.26	13.60	-0.80	10.4	2.6	0.25	10.70	0.30
Total			1370.5			1167.90		850.1			735.60	
Av.	168.12	2.90	85.65	19.97	0.28	72.99	-12.66	53.13	11.68	0.31	45.97	-7.15

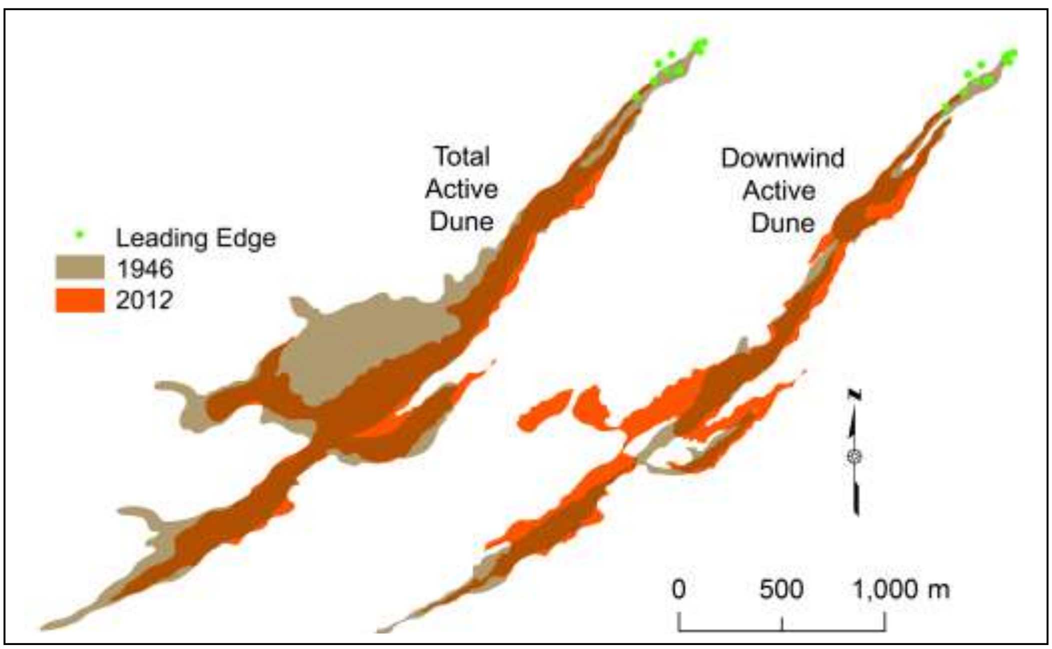
The following pages present examples of dune area trends, showing both total active dune and downwind active dune in comparing the dune boundaries on the earliest with the most recent imagery. The select examples include all six dunes that have had over 300 plants documented (see Figure 4). The downwind active dune encompasses virtually all occupied habitat and compare closely with species distribution maps produced in surveys. Tables and graphs that present all data for each of the 16 dunes are in Appendix B.

Figure 5. Total active dune (left) and downwind active dune (right) of Dune 8 (1946 and 2012)



Dune 8 migrated 638 m in 66 years while it declined in size of total and downwind dune area (Figure 5). It is one of the most topographically complex dune areas, composed of three blowout features side-by-side resembling three stair steps that rise to the southeast. It had two or three leading edges corresponding to each blowout bowl, but downwind expansion is blocked by a hill at all but the lowermost northwestern blowout. Starting in 2001, dune migration accelerated, and by 2012, the downwind dune area overlapped little with that of 1946. *Penstemon haydenii* has been found as far downwind as the 1994 leading edge, but colonization has not been found at more recent leading edges. In other words, the new zones of migrating downwind dune habitat have not been colonized in almost 20 years, whether because of habitat unsuitability or habitat adversity such as burial. The new zones of dune migration form gentle slopes where they may be subject to vegetation encroachment unless there is eventual formation of blowout features. This is the only *Penstemon haydenii* dune area that does not have additional occupied *P. haydenii* dunes located nearby, so there is no upwind seed source, although there are unoccupied blowouts located upwind that serve as sand sources. It is one of the six dunes having had over 300 plants.

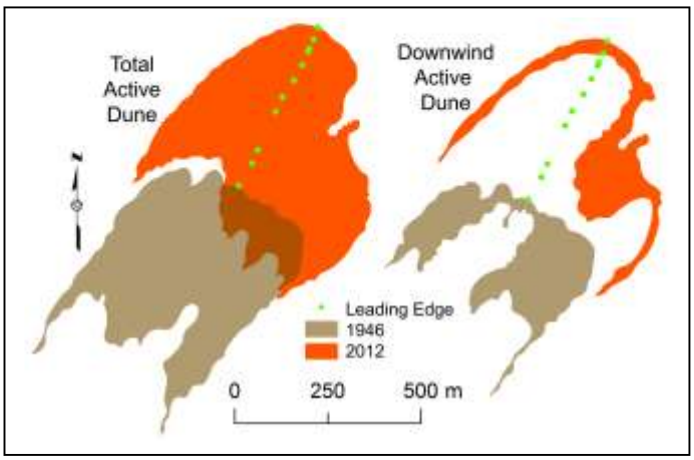
Figure 6. Total active dune (left) and downwind active dune (right) of Dune 15 (1946 and 2012)



By contrast, Dune 15 migrated little in 66 years and expanded in its downwind active dune area but declined in its total active dune area (Figure 6). It is relatively stable in location and size even though it has the steepest occupied dune habitat and has especially exposed, south-facing slopes among the 16 dunes. It was once a semi-continuous dune deposit, as seen in 1954, subsequently broken into two by 1994 when a giant central blowout formed, interrupting the continuity. It has been treated as two separate dunes in surveys of recent years. The largest eastern segment of Dune 15 has had the highest numbers of *Penstemon haydenii* plants every year of census, ranging from 3358 - 6317 plants in three different years. The lowest number was the most recent, in 2010. The highest numbers of plants are on the slip face slope and in a downwind trough at the base of the steep slope.

Dune 1 contrasts with Dune 8 in that it migrated unimpeded, and with a leading edge that has been more like a sheet than a narrow lobe. In 1946 the leading edge of Dune 1 was on the margin of Pathfinder Reservoir and in 2012 it was also on the reservoir margin, but sand has been deposited into the reservoir, shifting the shoreline. The downwind active dune habitat has continued to shrink as sand has been deposited into deeper and deeper water. Dune 1 has migrated 479 m in 66 years (Figure 7). It has had only one year of census, in which a total of 769 plants were documented in 2011.

Figure 7 (below). Total active dune (left) and downwind active dune (right) of Dune 1 (1946 and 2012)



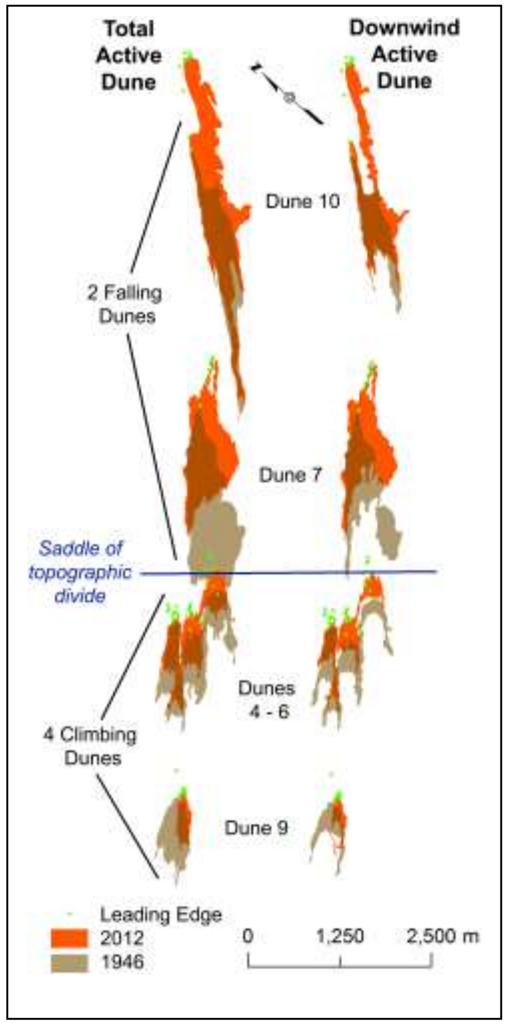


Figure 8 (right). Total active dune (left) and downwind active dune (right) of Dunes 4-10 (1946 and 2012). (Note the difference in scale of Figure 8 compared with previous figures. Note also that this figure has been rotated.)

The first three examples of *Penstemon haydenii* dune movements represent dunes moving in isolation of other occupied dunes. The fourth example of *P. haydenii* dune movements show dune habitat connectivity in a set of six dunes lying directly downwind and upwind of one another (Figure 8). It also graphically shows the effects of topographic interception for climbing dunes with their smaller total dune area on the upwind side of the Continental Divide (av. = 34.6 ac), as compared to the elongate falling dunes on the downwind side of the Continental Divide (av. = 184.4 ac). The dune that has had the highest *P. haydenii* census number in the series is Dune 7, followed by Dunes 4 and 5. Dune 10, the downwind dune, has the largest dune area but has had the lowest census numbers (Heidel 2012).

Comparison between the dune trend data and *Penstemon haydenii* population trend data is limited by the number of census records and the number of orthoimages from which to draw correlations. In the case of Dune 8, which has the most population trend data, it appears that population trends (Figure 9) may be inversely related to the rate of dune movement (Figure 10), unrelated to active dune area (Figure 11).

Figure 9. *Penstemon haydenii* population trends at Dune 8

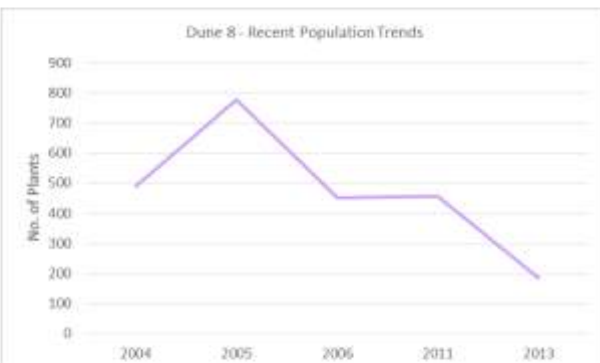


Figure 10. Rate of dune movement at Dune 8

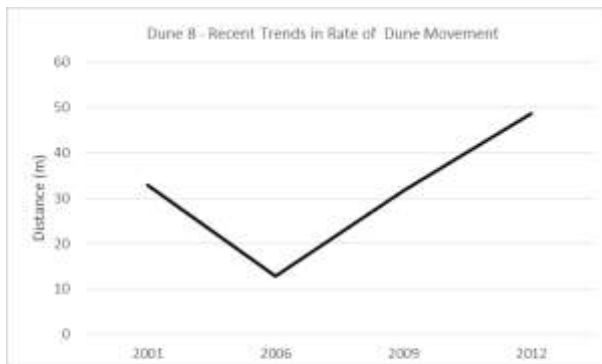
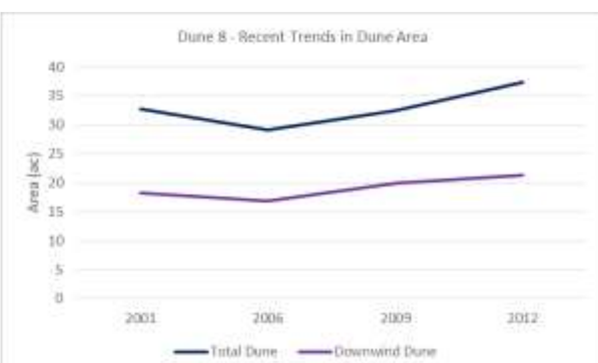


Figure 11. Active dune area trends at Dune 8



Discussion

Results indicate that the conditions required by *Penstemon haydenii*, namely active sand dunes, have existed continuously over time back to at least 1946. Wyoming habitat (the downwind dune area of active sand dunes) may have declined about 13.5% going back to at least the 1940's, but this level of change does not make them analogous to Nebraska habitat with magnitudes of habitat loss or complete disappearance over the same time period. In Wyoming, it appears that the habitat reductions at any one dune are compensated at least in part by asynchrony of changes among dunes across the landscape and the interconnection of many dunes.

There is one possible correlation between habitat trends and *Penstemon haydenii* population trends, a negative relation between population trend and dune movement rate as seen at Dune 8 (Figures 9-10). Results are consistent with the interpretation that dune destabilization and migration are associated with burial and erosion, at least in the short-term. The duration and severity of burial and erosion may determine whether or not dune migration is a cause of mortality. Results also point to dune stabilization events, in the case of Dune 7, where a blowout rim appeared to have formed by 1982. By 2003, it was one of the largest subpopulation, and is a possible case of dune stabilization that was also marked by retreat of the leading edge in ensuing years. These interpretations of the relationships between population trends and habitat trends are preliminary. In any case, the species is adapted to persist, if not expand and increase with habitat flux, as indicated by monitoring data and analysis of aerial imagery.

In 2006, botanists noted the widespread pattern of blowout rims breaching among *Penstemon haydenii* occupied habitat and were concerned by reduced census numbers associated with sand burial of downwind habitat in ensuing years. Even though the species seemed to disappear in deposition areas, one such area was excavated in 2013 between two aboveground plants and revealed the presence of seven live, buried underground plants. This raises the possibilities that the species survives prolonged burial, that population census numbers under-represent the number of genets, and that the levels of under-representation may differ between years. Thus, it is possible that established plants can persist below ground for at least part of the growing season at the time of census, confounding the completeness of any given census. In the absence of any known re-emergence data in such zones, or documentation of colonization in new sand deposits, key components of the population trend picture across the dynamic landscape are missing. In light of dune dynamics, it may be more valuable to document these phenomena than to conduct census without better information on them.

When surveys for *Penstemon haydenii* started in Wyoming, subpopulation boundaries were mapped as though they were static. There was no information on the rates of movement and fluxes in such habitat. From what we know now, subpopulation boundaries are subject to change and any given downwind dune area may include occupied habitat, buried habitat (which may or may not have plants surviving below), and newly-deposited unoccupied habitat. The downwind dune area as a mapping unit is a consistent and meaningful representation of species' potential distribution but only represents one point in time. The occupied habitat trends can be better documented by collecting additional GPS points in the field. The next orthoimagery collection of this area is scheduled for July 2015 (NAIP 1-m GSD collection), and those data can be used to update working distribution maps and refine dune movement rates. It might be ideal to conduct concerted population boundary mapping all in the same year as represented by orthoimagery from the same year.

The relationships between *Penstemon haydenii* downwind dune area and dune movement rate vary greatly between the different dunes. The fact that the average movement rates at 2.8 m/year is much less than the average rate of 8.4 m/year calculated for the Ferris Dunes overall (Gaylord 1982) raises questions on whether the specific dunes were the basis of difference, or whether the specific time intervals of aerial imagery (1944-1977 vs. 1946-2012) account for the difference. Nine of the dunes in this study were among the 35 dunes in the Gaylord work. One of the most stable dunes identified in this study relative to movement and aerial change is Dune 15, and as previously mentioned, it has supported the highest *P. haydenii* numbers. The fact that this same dune is in one of the most turbulent settings, steepest slopes and largest deposits indicates that habitat stability may be a balancing act between gravity and wind. On the other hand, the dune with the highest rate of movement is Dune 10, located at the downwind end of the Figure 8 dune series and with consistently low numbers of *P. haydenii* plants. It has gentle slopes, a breached blowout rim and high levels of burial. This relatively unstable, downwind dune may not contribute directly to species' viability in the short-term, but could be important over the long term if the species forms seed banks.

It is outside the scope of study objectives to determine if management practices influence habitat trends. There are man-made structures in the area including the Ferris town site, which operated as an oilfield town from 1920-1938 (BLM cultural archives, unpubl.), and old homesteads present in the same townships as occupied dunes. However, there were no straight-line patterns in digitized dune features as would be expected if influenced by fences, roads and land uses in general, even though there are undeveloped roads to the area and a pipeline that crosses between dunes. Only one of the 16 dunes has been strongly influenced by management, in the case of Dune 1 bordering the Pathfinder Reservoir. Its leading edge moved 479 m from the 1939 position at the reservoir margin, depositing sand that shifted the reservoir margin at a rate of 7.3 m/year. The currently occupied downwind active dune is less than 50 m wide along most its length, and extirpation is possible.

If *Penstemon haydenii* habitat loss in Wyoming is low, then the species' status and the case for recovery intervention as inferred from Nebraska data may warrant review. The analysis of historical aerial imagery documents that *P. haydenii* occupies dynamic sand dune systems in Wyoming, even though such habitat is far smaller in Wyoming than in the Nebraska Sandhills. Interpretations of current population and habitat data and trends, and their interactions, are tempered by the lack of life history data for Wyoming and a number of unknowns including colonization rates and patterns. Three lines of investigation would shed light on the relationships. There is no documentation of *P. haydenii* colonization in any of the new deposits, and it would be constructive to document the colonization phenomenon (e.g. at Dunes 8, 10 and 15). While the conditions that promote emergence of underground plants are still not clear, it might be constructive to do selective monitoring in years with wet springs where plant burial occurred in the past (e.g., Dune 7). It may be constructive to more closely-analyze the one occupied dune area having no intact rims, on the ground and in associated historic aerial imagery (not addressed in this study), to determine its relationships and bearing on the rest of dune areas. Localized, high-resolution stereo orthoimage collection (10-30cm GSD) could help elucidate relationships by allowing more conclusive downwind dune area delineation over time.

In summary, habitat of *Penstemon haydenii* appears to have persisted continuously for over 60 years as mobile habitat. The dunes cross a patchwork pattern of mixed public and private lands. Dune mobility increases the importance of landscape-scale management to maintain current conditions. Evidence of past threats has not been identified except for Pathfinder Reservoir construction, though there are many potential threats to the Wyoming populations (USDI Fish & Wildlife Service 2012). Those segments on BLM lands are addressed in current BLM planning documents, and there are magnitudes more threats on the non-BLM lands. The documented habitat dynamics are consistent with the borders that have been proposed for the Penstemon haydenii Area of Critical Environmental Concern. Although this study has not produced quantitative population and habitat standards for recovery, there are now data that present a case for addressing the dunes as series in a connected system warranting buffers around currently-occupied habitat and those areas immediately up- and downwind.

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