

Evaluating the effect of rainfall variability on vegetation establishment in a semidesert grassland

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Abstract Of the operations required for reclamation in arid and semi-arid regions, establishing vegetation entails the most uncertainty due to reliance on unpredictable rainfall for seed germination and seedling establishment. The frequency of successful vegetation establishment was estimated based on a land surface model driven by hourly atmospheric forcing data, 7 years of eddy-flux data, and 31 years of rainfall data at two adjacent sites in southern Arizona, USA. Two scenarios differing in the required imbibition time for successful germination were evaluated—2 or 3 days availability of sufficient surface moisture. Establishment success was assumed to occur if plants could germinate and if the drying front in the soil did not overtake the growth of seminal roots. Based on our results, vegetation establishment could be expected to fail in 32 % of years. In the worst 10-year span, six of ten plantings would have failed. In the best 10-year span, only one of ten was projected to fail. Across all assessments, at most 3 years in a row failed and 6 years in a row were successful. Funding for reclamation seeding must

be available to allow reseeding the following year if sufficient amount and timing of rainfall does not occur.

Keywords Southern Arizona · Land reclamation · Grass germination · Seeding failure

Introduction

The operations required to reclaim arid and semi-arid lands fall into several different categories: modifying topography (slope, contours, and drainage), creating appropriate surface composition (compaction, particle size, and origin of the final surface), and establishing vegetation. Of these categories, establishing vegetation entails the most uncertainty. Vegetation establishment is important for: reducing erosion from both wind and water (Guitierrez and Hernandez 1996; De Baets et al. 2009; Fehmi et al. 2008), improving public perception by reducing the visual impact (Hands and Brown 2002; Svobodova et al. 2012), allowing for productive reuse of the land for wildlife habitat or livestock grazing (e.g., Steinke and Majak 2010), and otherwise reintegrating disturbed lands into the existing landscape. Uncertainty in vegetation establishment comes primarily from reliance on unpredictable rainfall for germination and establishment.

While reliance upon rainfall is not the only option, irrigation is expensive and generally not more successful (Roundy et al. 2001) possibly because a high intensity/long duration of water application is needed to establish plants, and even when plants are established

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with irrigation, they can lack water hardiness and die when the irrigation is eventually removed (Josa et al. 2012). Irrigation can also benefit exotic weeds more than natives (e.g., Banerjee et al. 2006). Natural rainfall can allow the establishment of robust native or non-native vegetation albeit at densities similar to nearby undisturbed vegetation (e.g., Fehmi and Kong 2012). While in the past non-natives were preferred for their ability to establish in years with limited rainfall, natives are now more recommended due to their known long-term stability, resource value for wildlife, and better public acceptance (D'Antonio and Meyerson 2002). Non-natives are currently less acceptable due to potential economic losses due to their invasions off-site, increases in the ability of reclaimed lands to carry wildfire (McDonald and McPherson 2011), and other negative impacts (Hobbs and Cramer 2008).

To maximize the long-term positive impact of re-vegetation, a mixed plant community is needed that contains the same ratio of functional groups as a natural community in the same area. In addition to being self-sustaining, diversity increases the resiliency of the plant community to disturbance (Quijas et al. 2010). Where they occur, perennial grasses are often the primary contributors to surface stability and erosion prevention (Guitierrez and Hernandez 1996; De Baets et al. 2009) through their life form which is extensive, low to the ground, and with spreading, fibrous roots near the soil surface.

Cox and Jordan (1983) expected successful establishment of native perennial warm-season grasses only 10 % of the time (1 in 10 years) in arid to semi-arid southeastern Arizona, USA. This is similar to the estimates generated by Peters (2000) for central New Mexico. Establishment success for a seedling depends on the seminal root staying ahead of the soil drying front. When native warm-season (C4) grasses commonly planted in the southwestern USA germinate, they are supported by the seminal root (often also called the primary root) until the adventitious roots begin to grow. Because these grasses establish the plant crown near the surface of the soil, adventitious root growth can be suppressed by dry conditions (Hyder et al. 1971).

Other than the predictions mentioned above and research studies that rarely consider more than a few years (e.g., Woods et al. 2012), little work has occurred to better assess the chance of seeding success for arid areas. Other studies have shown that seedling recruitment is not

dependent solely on high rainfall years but instead on the amount and distribution of rainfall events (e.g., Peters 2000; Zimmerman et al. 2008; Thapa et al. 2012). Given the advances in both natural history information and in ease of computer modeling, Cox and Jordan's (1983) prediction about southern Arizona should be revisited. Modeling can resolve important management and ecological questions because it allows comparisons that are not possible in the field (Hardegee et al. 2010). The goal of this project is to estimate how frequently native perennial warm-season grasses may be established in southern Arizona using 31 years of historical rainfall event data. It is important to research the likelihood of vegetation establishment to better develop mitigation strategies and to allow appropriate budgeting for them.

Materials and methods

To estimate the frequency of successful establishment, we simulated soil moisture for a 31-year period using a land surface model. The inputs included detailed long-term precipitation event data, data on movement of moisture through the soil, and data on evaporation from the Santa Rita Experimental Range (described below). These data allowed analysis of moisture at the surface and at each soil layer as roots grew through them. Using real-world data was important because having valid input parameters remains the most difficult aspect of modeling seed germination (Flerchinger and Hardegee 2004), and correctly representing rainfall variability is critical for modeling soil moisture (Laio et al. 2001).

The specific practices selected for analysis included having seeded on 15 May (30 days ahead of the normal start of the monsoon season) onto bare soil in southern Arizona, USA. The seeds (generic native warm-season grasses described below) were assumed to be in the top 0–1 cm of the soil when the monsoon rains began. This was consistent with broadcast seeding in common use (Peppin et al. 2011). The soil type used in the simulations was a loamy sand because this soil texture was common in the region as well as being the primary soil type on a nearby mineland reclamation site. No existing vegetation was assumed at the time of the seeding (bare soil) which had the simplifying effect of having evaporation to be the primary evapotranspiration loss. Germination and establishment were evaluated over the first 21 days, so competition among seedlings was assumed

not to have an impact on plant growth or soil moisture in this period.

Rainfall data

Rainfall data (1980–2010, 31 years) came from gages 5 (31.8152 N, 110.8516 W, 1,163 m asl, 398 mm average annual precipitation) and 6 (31.8137 N, 110.8544 W, 1,215 m asl, 405 mm average annual precipitation) from the Santa Rita Experimental Range (SRER) which was roughly 45 km south of Tucson, AZ, USA (<http://www.tucson.ars.ag.gov/dap/>). The gages are 311 m apart and record the date, time, amount, and duration of each rainfall event. The gages and their operation were as described in Goodrich et al. (2008). The monsoon rainfall in this region was generally from convective cells which can result in different amounts of rainfall, even over short distances, so the data from each gage were evaluated separately.

Model integrating precipitation and eddy flux data to obtain soil moisture

Seven years (6 January 2004–31 December 2010) of eddy flux data were available, including the following measurements: temperature/relative humidity; photosynthetically active radiation; ground heat flux; soil temperature; precipitation; volumetric soil water content at 5, 10, 20, 30, 50, 70, 100, and 130 cm depths; wind velocity vector; sonic temperature and concentrations of water vapor; and carbon dioxide measurements (Scott et al. 2009; hereafter, flux tower data). The measurements were from the Santa Rita Mesquite Savanna site which was also located on the SRER (31.8214 N, 110.8661 W, 1,120 m asl). The soils at the site are uniform sandy loams.

To model the expected soil moisture from the 31 years (1980–2010) of precipitation data, we ran a land surface model, which was driven by hourly atmospheric forcing data. We calibrated the model's hydraulic parameters to match the observed soil moisture and surface energy and water fluxes from the flux tower data and then applied the optimized parameters to the 31-year precipitation data set.

The atmospheric forcing data to drive the model included: hourly downward shortwave and longwave radiation fluxes, precipitation, air temperature, humidity, pressure, and wind speed. These data were computed as distance-weighted averages of those at four surrounding

points of the 0.125 degree, gridded North American Land Data Assimilation System (NLDAS) surface atmospheric data (Mitchell et al. 2004). To check the accuracy of the NLDAS data, sensitivity experiments during the calibration period were conducted by replacing an individual variable of the flux tower data with that of the NLDAS data. Through this exercise, we found that NLDAS data overestimated wintertime precipitation and had the largest effect on the simulation of soil moisture, while other variables had less effect. We then replaced the NLDAS precipitation with the rainfall from gages 5 and 6 from the Santa Rita Experimental Range. Thus, for the period from 1980–2003, we ran the model using the optimized hydraulic parameters and the NLDAS atmospheric forcing with its rainfall data being replaced with data from gages 5 and 6.

The Noah land surface model was used in this study with multiple options for parameterization schemes of various land surface processes (Niu et al. 2011). There were only four soil layers in the standard model that was coupled with the Weather Research and Forecast model. In this study, to match the flux tower measurement depths, we divided the model soil into 16 soil layers (breaking at 2.5, 5, 10, 15, 20, 25, 30, 45, 50, 60, 70, 90, 100, 120, 130, and 200 cm). The model solved the one-dimensional Richards' equation to account for redistribution of soil moisture among these layers through diffusion and percolation processes. At the 2-m model bottom, we used a groundwater recharge rate, which was provided by a simple groundwater model, as the lower boundary condition to ensure a more precise simulation.

The soil hydraulic parameters for loamy sand were set up through a look-up table using the Clapp–Hornberger relationship (Clapp and Hornberger 1978). However, the amplitudes of the modeled soil moisture for most of the deep soil layers were too small to match observations, indicating the diffusion processes of soil water are relatively weak. The constant value 1.5×10^{-8} m/s was added to the diffusivity which resulted in comparable soil moisture for all measurement depths. The enhanced diffusivity accounted for extra diffusion of vaporized soil water under dry and hot conditions (Niu et al. 1997).

Assessment of germination

Our analysis assumed that the native, warm-season (C4) grass seeds were in the soil from 0–1 cm deep as suggested by Roundy et al. (1997), which corresponds

well to visual observations of seed depth after broadcast seeding on this soil type in this area. The seeds were assumed to remain available until they germinate rather than experiencing any other fate such as being eaten, buried, blown, or washed off site, etc. All seeds were assumed to germinate when exposed to suitable monsoon conditions (per Abbott and Roundy 2003). Wetting events that did not result in germination were assumed to cause no injury to these warm-season perennial grass seeds (Roundy et al. 1997). Germinating conditions that occurred before 15 May were not considered because this was before we assumed planting to occur. Germinating conditions that occurred after 30 September were assumed to result in seeding failure due to the lack of suitable growing conditions (cool weather) in October.

Two scenarios were evaluated for each of the rain gages—2 days of suitable conditions resulting in germination and 3 days of suitable conditions resulting in germination. Plants were counted as germinated if the water volume in the 0–2.5 cm layer stayed above $0.09 \text{ cm}^3/\text{cm}^3$ for 2 or 3 days (analyzed separately). This should be a conservative but general estimate for germination. An intermediate value for water volume (roughly twice the wilting point, $0.046 \text{ cm}^3/\text{cm}^3$, Laio et al. 2001) was chosen because the 0–2.5-cm layer dries quickly, but seeds can germinate if the relative humidity remains high at the soil surface (Wuest 2007). This generally fits with the observation of Roundy et al. (1997) that the surface soil becomes too dry within 1 day or less of the cessation of a storm.

The 2-day scenario was a more cautious interpretation of the available data on seed germination. Most warm-season perennial grasses germinate within 1.5 to 4 days of saturation of the surface soil at summer temperatures (Roundy and Biedenbender 1996). The 2-day scenario supported native warm-season grass species like *Bouteloua curtipendula* (Sideoats grama) which germinated and emerged within 2 days of suitable conditions—50 % in 1 day (Simanton and Jordan 1986). The authors considered this fast germination. Another study observed emergence of *B. curtipendula* beginning in 18 h and ending after 3 days (Frasier et al. 1985). While different authors have tested germination in different ways, most typically, the reported times were for saturated soil and our standard was dryer than that. Our 2-day germination scenario typically corresponded to one large or two medium-sized events.

The 3-day scenario was a more lenient estimate of the time needed for germination and corresponds more

closely to available data on native warm-season grass germination. Smith et al. (2000) found *Digitaria californica* (Arizona cottontop) required a minimum of 140 mm of water in a 3-day period for 50 % emergence. Wilson and Briske (1979) found *Bouteloua gracilis* (Blue grama) needed wet conditions for 2–4 days to germinate. After 2.3 days in wet field conditions, Abbott and Roundy (2003) found *B. curtipendula* had 90 % germination; *Leptochloa dubia* (Green sprangletop) had 75 %; *D. californica* had 70 %, and *Eragrostis intermedia* (Plains lovegrass) had 45 %. Our 3-day germination scenario typically corresponded with 2–2.5 days of rain.

Assessment of survival after germination:

Our analysis of survival was based on seminal root growth. Germinated plants die when seminal root growth does not keep up with the drying front in the soil which makes soil moisture the primary controlling factor for seedling mortality (Carren et al. 1987; Zimmerman et al. 2008; Perring and Hovenden 2012; Thapa et al. 2012). This process was important for 2–3 weeks after germination when 2–4 days of additional moisture was needed at the soil surface for development of the plant crown and adventitious roots (Carren et al. 1987; Roundy et al. 1993). The drying front was defined as the wilting point ($0.046 \text{ cm}^3/\text{cm}^3$) for a loamy sand (Laio et al. 2001).

The rate of 0.8 cm root elongation per day was chosen as a conservative estimate based on several studies of native warm-season perennial grasses. For *B. gracilis*, the seminal root grew 0.79 cm per day for the first 2 weeks (Carren et al. 1987). *B. curtipendula* averaged about 0.8 cm per day of seminal root elongation during the first 15 days (Roundy et al. 1993). In another study, Simanton and Jordan (1986) found an elongation rate of 0.97 cm per day for the first 7 days for *B. curtipendula*. Using the modeled soil moisture, root elongation was evaluated for 19 days after germination. This was when the seminal root reaches 15 cm soil depth. If sufficient water were available, plants may have initiated adventitious roots during our 19-day evaluation, but we evaluated soil moisture for the whole soil column and dryness below the wilting point would have affected adventitious roots as well as seminal roots. In our assessment, we checked the simulated water content of the soil column from the surface to the depth of the seminal root, and if the whole column was below the wilting point, the seeding was considered to have failed.

Table 1 Evaluation of plants taking 2 days to germinate at the gage 5 site

Success/failure	Year	Germination date	Minimum soil moisture cm ³ /cm ³ during root elongation through zone			
			Surface to 2.5 cm	2.5 to 5.0 cm	5.0 to 10.0 cm	10.0 to 15.0 cm
	1980	14 Aug	0.051	0.049	0.053	0.055
	1981	11 Jul	0.119	0.118	0.082	0.084
Failed ^a	1982	8 Jul	0.048	0.045	0.058	0.099
	1983	12 Jul	0.067	0.053	0.055	0.049
	1984	30 Jun	0.064	0.081	0.073	0.078
	1985	21 Jul	0.073	0.060	0.075	0.083
Failed ^b	1986	17 Jul	0.060	0.057	0.041	0.043
Failed ^b	1987	22 May	0.058	0.052	0.039	0.037
Failed ^c	1988	11 Jul	0.044	0.040	0.052	0.107
	1989	28 Jul	0.085	0.076	0.083	0.083
	1990	9 Jul	0.129	0.095	0.133	0.136
Failed ^c	1991	31 Jul	0.035	0.033	0.041	0.067
Failed ^b	1992	9 Jul	0.088	0.065	0.044	0.054
	1993	4 Aug	0.141	0.113	0.072	0.082
	1994	4 Sep	0.060	0.050	0.089	0.076
Failed ^c	1995	22 Aug	0.046	0.049	0.039	0.040
	1996	4 Jul	0.072	0.078	0.094	0.070
	1997	19 Aug	0.053	0.064	0.071	0.080
	1998	6 Jul	0.129	0.098	0.072	0.085
	1999	27 Jul	0.090	0.067	0.065	0.074
	2000	21 Jun	0.059	0.090	0.091	0.090
Failed ^c	2001	5 Aug	0.034	0.064	0.068	0.068
Failed ^c	2002	18 Jul	0.045	0.052	0.103	0.087
	2003	27 Jul	0.099	0.111	0.082	0.082
Failed ^c	2004	15 Jul	0.036	0.047	0.058	0.089
	2005	6 Aug	0.116	0.091	0.101	0.082
	2006	28 Jul	0.094	0.094	0.079	0.069
	2007	21 Jul	0.064	0.066	0.076	0.089
	2008	13 Jul	0.051	0.047	0.067	0.071
Failed ^d	2009	No germ				
	2010	31 Jul	0.075	0.056	0.054	0.054

Numbers at or below the wilting point (0.046 cm³/cm³) for this soil type are in bold. Of the 31 years evaluated, 20 years had successful establishment in the first 19 days after germination

^aToo little rain, hits wilting point at 2.5 to 5.0 cm

^bToo little rain, hits wilting point at 5.0 to 10.0 cm

^cToo little rain, hits wilting point at surface to 2.5 cm

^dNo germination

Results

The average germination date for the gage 5 2-day scenario was 20 July (Table 1), and for the 3-day scenario, it was 1 August (Table 2). The average germination dates for gage 6 2-day scenario was 19 July (Table 3), and for the 3-day scenario, it was 27 July (Table 4). In most years, there was little difference in germination date and success among the gages and the scenarios, but in a few years there were substantive

differences among the gages and treatment germination dates (Fig. 1). In 2001, the expected germination in the 3-day evaluation of gage 5 was 111 days later than the 2-day evaluation of gage 6.

For the gage 5 two-day scenario (Table 1), 35 % of the years failed to have successful establishment, and 29 % failed for the 3-day scenario (Table 2). For the gage 6 two-day scenario (Table 3), 29 % of the years failed, and 35 % failed for the 3-day scenario (Table 4). This gives an average failure rate of 32 %. The years

Table 2 Evaluation of plants taking 3 days to germinate at the gage 5 site

	Success/ failure	Year	Germination date	Minimum soil moisture cm ³ /cm ³ during root elongation through zone			
				Surface to 2.5 cm	2.5 to 5.0 cm	5.0 to 10.0 cm	10.0 to 15.0 cm
	Failed ^a	1980	15 Aug	0.048	0.043	0.053	0.051
		1981	12 Jul	0.104	0.121	0.075	0.084
		1982	23 Jul	0.068	0.063	0.061	0.058
	Failed ^a	1983	13 Jul	0.064	0.044	0.055	0.046
		1984	19 Jul	0.091	0.103	0.098	0.096
		1985	22 Jul	0.070	0.060	0.100	0.077
	Failed ^b	1986	18 Jul	0.047	0.057	0.039	0.043
		1987	6 Aug	0.066	0.085	0.068	0.072
	Failed ^c	1988	12 Jul	0.035	0.040	0.085	0.108
		1989	29 Jul	0.074	0.076	0.083	0.078
		1990	10 Jul	0.101	0.095	0.133	0.130
		1991	10 Aug	0.055	0.071	0.066	0.058
	Failed ^c	1992	13 Jul	0.046	0.042	0.044	0.064
		1993	5 Aug	0.141	0.097	0.072	0.086
		1994	5 Sep	0.049	0.050	0.081	0.076
		1995	30 Sep	0.064	0.062	0.053	0.051
	Failed ^c	1996	16 Jul	0.042	0.043	0.048	0.051
		1997	16 Sep	0.054	0.062	0.062	0.052
		1998	7 Jul	0.105	0.098	0.072	0.125
		1999	28 Jul	0.085	0.067	0.065	0.074
		2000	25 Jun	0.055	0.071	0.077	0.075
	Failed ^b	2001	10 Oct	0.057	0.051	0.041	0.039
		2002	25 Jul	0.106	0.078	0.075	0.085
		2003	28 Jul	0.096	0.123	0.078	0.082
	Failed ^{a,d}	2004	17 Aug	0.049	0.044	0.044	0.039
		2005	7 Aug	0.103	0.091	0.092	0.082
		2006	29 Jul	0.096	0.083	0.074	0.067
		2007	22 Jul	0.056	0.063	0.081	0.083
		2008	22 Jul	0.099	0.071	0.049	0.062
	Failed ^c	2009	No germ				
		2010	1 Aug	0.057	0.051	0.049	0.054

Numbers at or below the wilting point (0.046 cm³/cm³) for this soil type are in bold. Of the 31 years evaluated, 22 years had successful establishment in the first 19 days after germination

^aToo little rain, hits wilting point at 2.5 to 5.0 cm

^bToo little rain, hits wilting point at 5.0 to 10.0 cm

^cToo little rain, hits wilting point at surface to 2.5 cm

^dGermination too late in season

^eNo germination

where establishment failed do not always overlap. For gage 5, there were 6 years where the seeding failed for both scenarios (19 % failure rate), and for gage 6, there were only 4 years (13 % failure rate) where it failed for both scenarios (Table 5). These same 4 years also failed for gage 5, giving a failure rate common across both gages and both scenarios of 13 %.

The worst 10-year span was gage 5 for the 2-day scenario where between 1986 and 1995, six of ten plantings would have failed (Table 1). The best 10-

year span was gage 6 for the 3-day scenario where, between 1998 and 2007, only one of ten was projected to fail (Table 4). At most, 3 years in a row failed, and 6 years in a row were successful.

Discussion

Our modeling results showed six times more potential for seeding success (68 %) than was expected from the

Table 3 Evaluation of plants taking 2 days to germinate at the gage 6 site

Success/ failure	Year	Germination date	Minimum soil moisture cm ³ /cm ³ during root elongation through zone			
			Surface to 2.5 cm	2.5 to 5.0 cm	5.0 to 10.0 cm	10.0 to 15.0 cm
	1980	14 Aug	0.055	0.051	0.055	0.057
	1981	11 Jul	0.117	0.122	0.095	0.094
Failed ^a	1982	8 Jul	0.048	0.044	0.057	0.102
	1983	12 Jul	0.065	0.051	0.053	0.048
	1984	30 Jun	0.069	0.084	0.075	0.095
	1985	16 Jul	0.063	0.118	0.081	0.102
Failed ^b	1986	17 Jul	0.057	0.054	0.042	0.043
Failed ^b	1987	22 May	0.053	0.048	0.037	0.036
Failed ^a	1988	11 Jul	0.047	0.042	0.055	0.107
	1989	28 Jul	0.083	0.076	0.083	0.067
	1990	10 Jul	0.132	0.098	0.135	0.137
	1991	9 Aug	0.071	0.071	0.063	0.063
Failed ^{b,c}	1992	10 Jul	0.090	0.064	0.044	0.053
	1993	4 Aug	0.137	0.113	0.072	0.084
	1994	4 Sep	0.057	0.051	0.089	0.079
Failed ^c	1995	22 Aug	0.041	0.044	0.036	0.040
	1996	4 Jul	0.060	0.072	0.092	0.067
	1997	19 Aug	0.051	0.062	0.071	0.080
	1998	6 Jul	0.125	0.096	0.072	0.082
	1999	27 Jul	0.095	0.067	0.062	0.068
	2000	24 Jun	0.066	0.071	0.084	0.081
Failed ^c	2001	22 Jun	0.031	0.035	0.030	0.034
Failed ^c	2002	18 Jul	0.044	0.051	0.100	0.087
	2003	27 Jul	0.095	0.107	0.080	0.077
	2004	30 Jul	0.065	0.070	0.048	0.056
	2005	6 Aug	0.092	0.091	0.101	0.083
	2006	28 Jul	0.094	0.094	0.078	0.069
	2007	21 Jul	0.064	0.067	0.076	0.089
	2008	13 Jul	0.051	0.047	0.067	0.070
Failed ^d	2009	No germ				
	2010	31 Jul	0.075	0.056	0.054	0.054

Numbers at or below the wilting point (0.046 cm³/cm³) for this soil type are in bold. Of the 31 years evaluated, 22 years had successful establishment in the first 19 days after germination

^aToo little rain, hits wilting point at 2.5 to 5.0 cm

^bToo little rain, hits wilting point at 5.0 to 10.0 cm

^cToo little rain, hits wilting point at surface to 2.5 cm

^dNo germination

^eAlso failed 5 May which is outside the planting window

10 % estimate by Cox and Jordan (1983) for southern Arizona. While this may show substantial potential for reclamation in most years, there are numerous factors, such as germination response, root growth, and other sources of mortality, that bear further consideration.

The germination periods of 2 or 3 days which we assumed for analysis do not necessarily reflect the full scope of plant responses in real-world situations. For instance, non-germinating rains (not long enough in duration) that cause more than 1 day of adequate soil

moisture can reduce seed viability (Emmerich and Hardegree 1996). But less than 1 day of soil moisture before the eventual germinating rain can prime seeds and allow them to germinate faster than unexposed seeds once germinating rains occur (Emmerich and Hardegree 1996). In addition, a small amount of the native grass seed (1–2 %) will not germinate until the second or third germinating rain (Abbott and Roundy 2003) which is also not included in the model. These factors were not included because not enough information was available

Table 4 Evaluation of plants taking 3 days to germinate at the gage 6 site

Success/ failure	Year	Germination date	Minimum soil moisture cm ³ /cm ³ during root elongation through zone				
			Surface to 2.5 cm	2.5 to 5.0 cm	5.0 to 10.0 cm	10.0 to 15.0 cm	
Failed ^a	1980	15 Aug	0.051	0.045	0.055	0.054	
	1981	12 Jul	0.110	0.122	0.086	0.094	
	1982	23 Jul	0.077	0.069	0.067	0.064	
Failed ^a	1983	13 Jul	0.060	0.043	0.053	0.046	
	1984	1 Jul	0.066	0.077	0.075	0.112	
	1985	20 Jul	0.099	0.078	0.081	0.085	
Failed ^b	1986	18 Jul	0.045	0.054	0.039	0.043	
	1987	6 Aug	0.060	0.078	0.066	0.069	
Failed ^b	1988	12 Jul	0.037	0.042	0.092	0.115	
	1989	29 Jul	0.075	0.076	0.083	0.063	
	1990	10 Jul	0.105	0.098	0.135	0.128	
Failed ^c	1991	10 Aug	0.055	0.071	0.061	0.060	
	1992	10 Jul	0.075	0.054	0.044	0.080	
	1993	5 Aug	0.137	0.097	0.072	0.083	
Failed ^d	1994	5 Sep	0.048	0.051	0.082	0.079	
	1995	30 Sep	0.065	0.063	0.056	0.057	
Failed ^c	1996	16 Jul	0.038	0.040	0.046	0.051	
Failed ^d	1997	16 Sep	0.052	0.061	0.062	0.052	
	1998	7 Jul	0.102	0.096	0.071	0.123	
Numbers at or below the wilting point (0.046 cm ³ /cm ³) for this soil type are in bold. Of the 31 years evaluated, 23 years had successful establishment in the first 19 days after germination	1999	28 Jul	0.085	0.064	0.062	0.068	
	2000	25 Jun	0.054	0.071	0.077	0.077	
	2001	17 Jul	0.066	0.062	0.061	0.051	
^a Too little rain, hits wilting point at 2.5 to 5.0 cm	2002	25 Jul	0.098	0.074	0.073	0.084	
	2003	28 Jul	0.091	0.119	0.077	0.077	
^b Too little rain, hits wilting point at 5.0 to 10.0 cm	Failed ^c	2004	17 Aug	0.044	0.041	0.042	0.038
	2005	7 Aug	0.103	0.091	0.092	0.083	
^c Too little rain, hits wilting point at surface to 2.5 cm	2006	29 Jul	0.096	0.083	0.074	0.067	
	2007	22 Jul	0.056	0.063	0.081	0.083	
^d Germinated too late in season for successful establishment	Failed ^c	2008	22 Jul	0.099	0.070	0.049	0.062
	Failed ^e	2009	No germ				
^e No germination	2010	1 Aug	0.057	0.051	0.049	0.054	

to determine the expected average outcome, and the magnitude of the effect on reclamation success would likely be small.

The period after germination is similarly more complex than our model represents, although we have incorporated plant death due to lack of rain after germination. These deaths are similar to those observed by Abbott and Roundy (2003) who found two sowing dates in two separate years where the drying front exceeded seminal root depth for native perennial grasses. The complexity

comes in because their field data did not show 100 % mortality but instead had 0.6 % and 7.9 % survival. While this may not result in a stand of vegetation that allows one to claim reclamation success, even with sufficient water, survival rates of native perennial grasses are not near 100 % in arid and semi-arid areas. With 32 days of available water (the drying front did not exceed the seminal root depth), there was 28 % survival of *B. curtipendula*, 27 % survival of *L. dubia*, 10 % survival of *D. californica*, and 11 % survival of *E.*

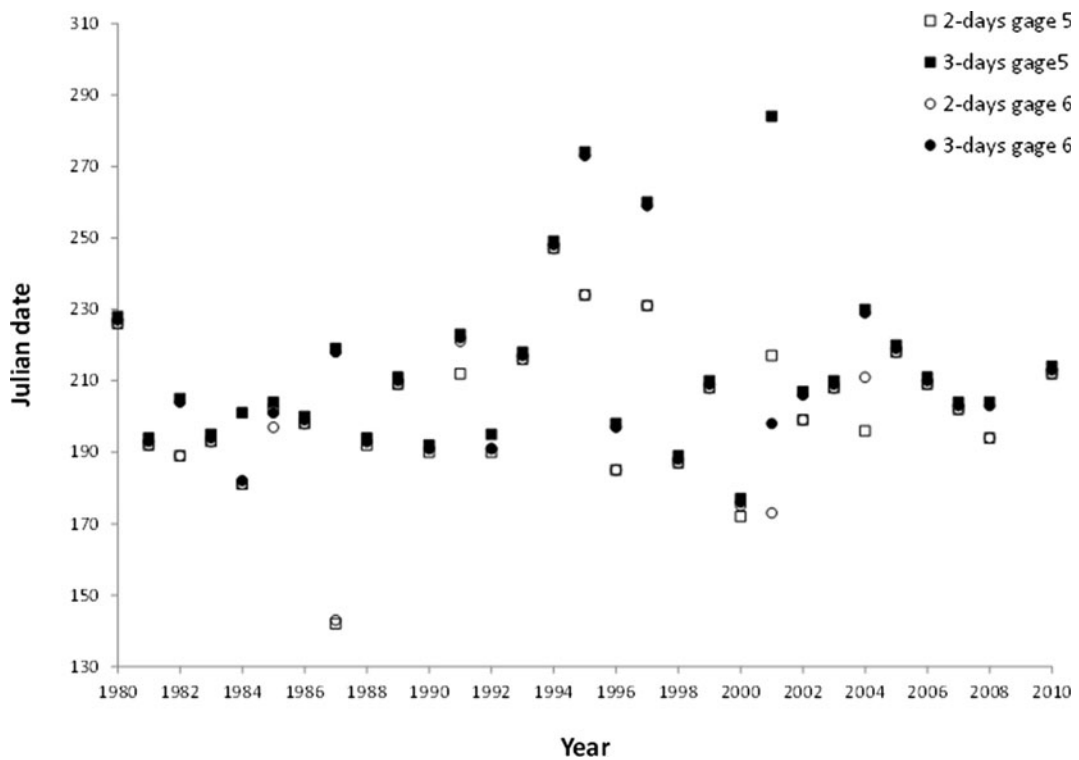


Fig. 1 Graph of the germination dates by year from 1980 to 2010. Julian date 150 is 29 May, 200 is 18 July, and 250 is 6 Sept

intermedia (Abbott and Roundy 2003). Nor are low survival rates unique to Arizona. In a study in Wyoming, Chambers (2000) found an overall survival rate of 1 % for seeded plants. Pyke (1990) had less than 1 % on a study in Utah, and James et al. (2011) had less than 9 % in Oregon. Given the relatively low survival rates of these common native perennial grasses, small differences may be more important than they appear, although poor survival possibly can be managed in the field by increasing the seeding rate or changing seed sources to more drought-tolerant collections.

The bottleneck for revegetation appears to be primarily in the establishment phase which occurs in the

weeks following germination. This appears applicable across many different systems, including Minnesota (Fay and Shultz 2009), Utah (Pyke 1990), and New Mexico (Peters 2000), although other studies from Wyoming (Chambers 2000) and Oregon (James et al. 2011) found out that mortality primarily occurred between germination and emergence.

In the period after germination, elongation rate of the seminal root and adventitious root initiation are the important factors for survival. *B. curtipendula* averaged about 0.8 cm per day of seminal root elongation, but the lengths varied 0.5–1.1 cm per day, depending on the amount and frequency of water with faster

Table 5 The overlap (consistency) among establishment failure across the gages and germination scenarios

		Gage 5 site		Gage 6 site	
		2-day	3-day	2-day	3-day
Overlap	Failures	11	9	9	11
	Gage 5 site				
	2-day	–	6	9	6
	3-day	6	–	5	8
	Gage 6 site				
	2-day	9	5	–	4
	3-day	6	8	4	–
Average germination date		20 Jul	1 Aug	19 Jul	27 Jul

elongation associated with more water (Roundy et al. 1993). For *B. curtipendula*, adventitious roots initiated on day 9 when watered every 3 days compared with day 13 when only watered on days 1 and 7 (Roundy et al. 1993). This would trigger the need for 2–4 days of available surface moisture to foster adventitious root elongation. *B. gracilis* is similar in that it needs wet conditions 2–8 weeks after germination to allow adventitious root establishment (Frasier et al. 1984). The variability of root elongation rates, the lack of studies on the non-genetic causes of rate differences, and inherent real-world variability in soil conditions make it difficult to know how they would change the outcome of our analysis.

Hovenden et al. (2008) found that the primary driver of seedling survivorship in a climate change scenario was soil moisture and that warming and CO₂ increases only affected survivorship indirectly through changing soil moisture. Notaro et al. (2012) predicted that southern Arizona will have warmer and dryer weather in the future but that much of this will be decreased winter precipitation which may have a limited impact on the dominant warm-season (C4) perennial grasses such as those modeled in this study. Consistent with Perring and Hovenden (2012), the total annual rainfall appears only slightly correlated with our predicted seeding success or failure. A logistic regression analysis showed that total seasonal precipitation was a significant predictor of germination success ($p=0.027$), but the analysis accounted for little of the variability (Nagelkerke $R^2=0.059$). The 6 years with the lowest rainfall (below 300 mm compared with a 400 mm average) had a 50 % failure rate which is more than the average rate of 32 %. The six years with the highest observed average rainfall (above 465 mm) had a 33 % failure rate. The distribution of rainfall events is clearly a variable that benefits seeds or seedlings, but larger event sizes during the growing season might not increase establishment. Once a storm event saturates the soil, a higher intensity event may not benefit seedling establishment because the seedlings are unable access moisture which has infiltrated deeper in the soil column and the excess water is lost as runoff. Plant establishment is sensitive to small changes in rainfall timing which is not well specified in predictions of future rainfall. Our observation of the common presence of events conducive to seeding success across the range of annual rainfall values makes it appear that warm-season perennial grasses may not be at risk from the kinds of changes predicted by Notaro et al. (2012).

The overall management implication for this study is that funds for reseeding must be available for at least a second year. This will allow reseeding the following year if there is a reclamation failure the year before. Further funds/reseeding effort may be needed because seeding failure 3 years in a row appears possible. A variety of species in a diverse mix, while often recommended for creation of a stable and self-sustaining plant community, may also help reduce the risk of seeding failure in years with marginally poor rainfall distribution because different species have different water and time requirements for germination. Field experiments would verify the germination and establishment modeling results and allow better predictions of seeding success.

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