Transplanting Sedges (*Carex* spp.) in Southwestern Riparian Meadows

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Abstract

The success of revegetation efforts in southwestern U.S. riparian meadows has been limited because natural recolonization is often poor and little is known about establishment of transplanted native meadow species such as sedges. To evaluate their potential use in riparian restoration, the survival and growth of transplanted wildlings of three sedge species, *Carex lanuginosa* (woolly sedge), *C. nebrascensis* (Nebraska sedge), and *C. rostrata* (beaked sedge), were assessed. Transplanting occurred during two seasons (summer and fall) using two transplant sizes (295 and 680 cm^3) at seven montane meadow sites in Arizona. Survival was similar among species, but shoot numbers were greater for *C. lanuginosa* (12.7 shoots/wildling) compared with *C. nebrascensis* (5.5 shoots/wildling) and *C. rostrata* (7.9 shoots/wildling). Survival was significantly greater for the summer transplant season (55.1%) versus fall (24.1%). Survival and growth were greater for the larger transplant size (46.1% large vs. 33.0% small; 8.1 shoots/wildling large vs. 6.4 small). Wildling survival was related to depth to groundwater for each species. Survival was highest for *C. lanuginosa* (78.6%), *C. nebrascensis* (88.2%), and *C. rostrata* (64.3%) where the groundwater depth was −48 to −60, −28 to −47, and −8 to −27 cm, respectively. These results suggest that restoration will be most successful if transplanting occurs in summer, using large wildling transplants when under stressful conditions such as waterlogged or dry soils, and when species are planted at appropriate groundwater depths.

Key words: revegetation, transplants, sedges, *Carex*, meadow restoration, riparian.

Introduction

In the arid southwest United States, the abundance of water and nutrients and the vigorous plant growth characteristic of montane riparian meadows contrast sharply with conditions in surrounding uplands. These characteristics enable meadows to provide valuable ecological and economic benefits, including habitat for terrestrial and aquatic wildlife, flood attenuation, water storage and purification, nutrient cycling, forage production, and recreational opportunities (Patten & Judd 1970; Carter 1986; Arizona Department of Environmental Quality 1994). Riparian meadows are typified by fine-textured soils and channel substrates, shallow water tables, and anaerobic soils (Kauffman et al. 1997). Sedges (*Carex* spp.) are especially well adapted to these conditions and play a key role in maintaining meadow integrity (Winward 1986). Sedges have extensive root systems that bind streambank soils (Manning et al. 1989; Kleinfelder et al. 1992). Their foliage forms a protective cover over the soil surface during high flows and fosters streambank development through sediment entrapment (Clary et al. 1996).

The impacts of road construction, improper grazing, and water diversions have resulted in deleterious alterations of the hydrology, geomorphology, soils, and vegetation of many southwestern riparian meadows. Channel incision often ensues, water tables drop, and the subsequent shift from hydric to mesic conditions leads to a decline of sedges and other native riparian graminoids (Prichard et al. 1993). Meadow restoration activities seek to restore channel integrity, raise water tables, improve water quality, and enhance wildlife habitat (Shaw et al. 2000). Given the fine-textured nature of meadow soils, reestablishment of native herbaceous vegetation is crucial to maintenance of restored channels (Allen 1978; Lyons et al. 2000). Although successful natural revegetation after restoration activities or removal of stressors (e.g., improper grazing) can occur, this process depends on the presence of an ample supply of seed or rootstocks, environmental cues that trigger germination, and suitable conditions for seedling and rhizome growth (Kadlec & Wentz 1979; Galatowitsch & Biederman 1998). Sedges generally reproduce vegetatively, although establishment from seed may occur on disturbances if a seedbank is present and conditions are favorable (Bernard 1990; van der Valk et al. 1999). Consequently, recolonization after restoration may be slow or nonexistent if sedge rootstocks have been eliminated from a site (Galatowitsch & van der Valk 1996; Yetka & Galatowitsch 1999).

Despite their importance to meadow function, little is known about revegetation strategies for sedges in restoration projects. This is particularly true of montane species because few transplanting trials have been performed. Failure to seed on suitable seedbeds and inherently low

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seed viability in many sedge species likely explains why reseeding has generally been unsuccessful (van der Valk et al. 1999). Moreover, if the planting site is subject to high physical stress, such as erosion and siltation (as would be expected on streambanks undergoing restoration), seeding is likely to be less successful than transplanting (Allen 1978; Kadlec & Wentz 1979). Because sedge reproduction is generally more successful via rhizomes in unstable environments, transplanting wildlings (root plus shoot material removed from parent plants in healthy meadows) may be an efficient and effective method for reestablishing these species.

Transplanting season, wildling size, and depth to groundwater might all affect successful wildling establishment in riparian meadows, and the influence of these factors on the transplant performance of southwestern riparian sedges has not been addressed. Because wildling sources are limited, it is necessary to quantify the amount of transplant material required for successful establishment. The season during which transplanting occurs has been shown to dramatically affect the survival and growth of sedge transplants (Yetka & Galatowitsch 1999). Sedges reallocate carbohydrates and nutrients during phenological development as physiological needs shift among shoot and root growth, flowering and seed production, and storage (Auclair 1982; Steele et al. 1984), resulting in different levels of tolerance to transplanting stress during the year. Likewise, seasonal variations in environmental factors such as groundwater levels, soil moisture, and temperature alter establishment conditions at revegetation sites.

Depth to groundwater (or height of standing water) has been identified as a key determinant of herbaceous species patterns within natural riparian meadows (Wilson 1969; Allen-Diaz 1991; Castelli et al. 2000), and its influence on the performance of sedge transplants has been documented in other regions (Comes & McCreary 1986; Yetka & Galatowitsch 1999).

The objectives of this study were to assess the establishment success of wildlings of three sedge species transplanted during two seasons and using two transplant sizes and to determine whether a relationship exists between transplant survival and depth to groundwater for these three sedges. These objectives were addressed through field transplanting trials conducted in 1999 and 2000 at seven meadow restoration sites in northern and eastern Arizona using three sedge species common in southwestern riparian meadows: *Carex lanuginosa* (woolly sedge), *C. nebrascensis* (Nebraska sedge), and *C. rostrata* (beaked sedge).

Materials and Methods

Study Sites

Transplanting trials were conducted on seven stream reaches in five montane riparian meadows. These meadows are located in northern and eastern Arizona at elevations between 2,120 and 2,375 m (Table 1). Adjacent upland vegetation at all sites was dominated by *Pinus ponderosa* (ponderosa pine). Each meadow had experienced channel incision resulting in lowered water tables, poorly vegetated streambanks, and a shift in vegetative composition toward mesic species such as *Poa pratensis* (Kentucky bluegrass). Meadow soils were mollisols, with the exception of those at Hoxworth Springs, which were alfisols and entisols. The stream at Hoxworth Springs was not connected to groundwater but instead flowed over a restricting clay layer (A. Springer 2001, personal communication).

Riparian restoration efforts were underway at each meadow at the time of transplanting. These efforts included bank shaping and channel reconfiguration at two sites (Hoxworth Springs sites 1 and 2), bank shaping and installation of artificial riffle formations at four sites (Boggy Creek sites 1 and 2, Wildcat Creek sites 1 and 2), and installation of artificial riffle formations at one site (Lofer

Table 1. Attributes of sedge wildling transplanting sites.

Transplant Site	*Latitude and Longitude*	*Ownership*	*Elevation (m)*	*Parent Geology*	*Soil Type*
Boggy Creek 1	33°45′10′′N, 109°27′14′′W	Apache-Sitgreaves National Forest	2,330	Volcanic[a]	Aquic cumulic cryoboroll
Boggy Creek 2	33°45′11′′N, 109°27′15′′W	Apache-Sitgreaves National Forest	2,335	Volcanic	Aquic cumulic cryoboroll
Hoxworth Springs 1	35°02′40′′N, 111°34′08′′W	Coconino National Forest	2,115	Sedimentary[b]	Mollic cryofluvent
Hoxworth Springs 2	35°02′39′′N, 111°34′08′′W	Coconino National Forest	2,120	Sedimentary	Mollic cryoboralf
Lofer Cienega	33°47′35′′N, 109°40′25′′W	White Mtn. Apache Reservation	2,375	Volcanic	Aquic cumulic cryoboroll
Wildcat Creek 1	33°44′17′′N, 109°28′04′′W	Apache-Sitgreaves National Forest	2,330	Volcanic	Argiaquic cryoboroll
Wildcat Creek 2	33°44′22′′N, 109°28′07′′W	Apache-Sitgreaves National Forest	2,335	Volcanic	Aquic cumulic cryoboroll

[a] Volcanic rocks (middle Miocene to Oligocene).
[b] Kaibab limestone (Permian).

Cienega). After site preparation, streambanks were left with little vegetation and unconsolidated soils were present on sites where bank shaping was performed. To prevent damage to restored areas from high *Cervus elaphus* (elk) populations, elk-proof exclosures were either constructed or were already in place at each site.

Experimental Design

The experimental design for field transplanting was a three-factor randomized complete block design to test the effects of species, season of transplant, and transplant size on wildling performance after transplanting. The species factor had three levels (*C. lanuginosa*, *C. nebrascensis*, and *C. rostrata*), the season factor two levels (summer and fall), and the size factor two levels (small and large). Each treatment combination at the seven transplant sites received a row of eight wildlings. Transplant site served as a blocking factor. The experimental design for greenhouse transplanting was three-factor randomized design similar to the field except that the blocking factor (transplant site) was not included and the experimental units were individual sedge transplants and not entire rows of transplants.

Transplant Materials

The three species selected for the field transplant trials are found in riparian meadows throughout western North America (Hermann 1970). All are highly rhizomatous and important bank stabilizers (Manning et al. 1989; Hurd et al. 1992). Although their habitats overlap and they frequently occur in intermixed stands, previous research suggests *C. nebrascensis* is most tolerant of lower water tables (Allen-Diaz 1991; Sala & Nowak 1997), whereas *C. rostrata* is most tolerant of saturated anaerobic conditions (Hansen et al. 1995; Law et al. 2000).

Transplanting

Sedge wildlings were collected from healthy sedge stands in nearby riparian meadows during summer and fall 1999 using a soil core extractor (Core Soil Sampler, Art's Manufacturing and Supply, American Falls, ID, U.S.A.). The core removed included a sedge plant with one to three shoots and a portion of its root system. Use of the soil core extractor permitted relatively easy extraction of uniform transplants of two sizes. The small size was 5 cm diameter by 15 cm deep (approximately 295 cm^3), and the large size was 7.6 cm diameter by 15 cm deep (approximately 680 cm^3). To minimize transpiration and water stress, aboveground shoots were pruned to a height of 15 cm and extracted wildlings were kept in the plastic soil core inserts or were wrapped in plastic bags and kept moist and shaded until transplanting. Most wildlings were transplanted within 3 hr of extraction, with all wildlings transplanted within 16 hr of extraction.

Transplanting occurred in 1999 during two seasons: summer (late June/early July before the summer rains) and fall (late October/early November). These transplant seasons were chosen to evaluate plant response during different developmental stages and because meadow soils are normally dry enough to permit restoration activities during these times.

A total of 672 wildlings were transplanted during the study. Wildlings were planted in rows (eight wildlings of a particular species, season, and size per row) oriented perpendicular to the stream channel and extending from 0.25 m into the water to 3.75 m from the water's edge with 0.5-m spacing between wildlings and rows. This planting configuration ensured that wildlings within each row were exposed to a range of groundwater depths. With the exception of light watering during planting to eliminate air pockets in the soil, no further assistance (watering, fertilization, weeding) was given to wildlings after transplanting.

The effects of transplanting versus site conditions on plant mortality were evaluated by comparing plant survival in the field with survival in the greenhouse. Six wildlings of each treatment combination were transplanted into a greenhouse at the Rocky Mountain Research Station in Flagstaff, Arizona coincident with field transplanting. In the greenhouse, wildlings were transplanted into 1-gallon plastic pots filled with equal portions of perlite, vermiculite, and peat moss. Greenhouse temperatures were maintained at 25°C during the day and at 15°C during the night, with relative humidity levels between 20% and 40%. Pots were kept well watered, and plant response was followed for 16 weeks.

Measurements

Survival (out of eight wildlings), number of shoots per surviving wildling, and average shoot height were measured on each row 1 year after transplanting to assess transplant response (i.e., summer transplants were assessed in summer 2000 and fall transplants in fall 2000). Wildlings were considered alive if at least one green shoot was present. Shoot numbers were determined by counting all shoots of the target sedge species within a 0.5 × 0.5-m quadrat around each wildling. Heights of all shoots within the quadrat were measured to the nearest millimeter. Aerial cover of target sedge species and all other plants was visually estimated for each wildling row immediately after transplanting and 1 year later. A control plot, where restoration activities were performed but no transplanting occurred, was established at each site to assess changes in sedge and other plant cover between 1999 and 2000. Survival of wildlings transplanted to the greenhouse was assessed after at least 16 weeks had passed.

Environmental factors important for wildling establishment and growth were measured at all transplant sites, including groundwater depth, soil moisture, and soil properties. Monthly assessments of groundwater depths and soil moisture were initiated coincident with summer transplanting in June or July 1999 and were continued through

the 1999 and 2000 growing seasons. Two piezometers were installed at each site 0.5 and 3.0 m from the water's edge to monitor groundwater levels (Girault 1990). Soil moisture in the upper 15 cm of the soil profile adjacent to each piezometer was determined using the gravimetric method (Lowery et al. 1996). A soil pedon description (Soil Survey Staff 1984) was also completed for each transplant site. Laboratory Consultants, Ltd. (Lordsburg, NM, U.S.A.) analyzed soil samples from each horizon for soil texture using the hydrometer method and percent organic matter using the Walkly-Black wet oxidation method (Soil Science Society of America 1994). Soil bulk density for the upper 15 cm of the soil profile on both upper and lower streambanks (three samples from each) was determined at each site (Arshad et al. 1996).

To test relationships between individual wildling survival and depth to groundwater, estimates were made of the greatest depth to groundwater experienced by each summer transplant during the growing season of 1999 using a rotating laser level (model RL-H, Topcon Laser Systems, Inc., Pleasanton, CA, U.S.A.). The elevations of the soil surface at each wildling and the upper and lower piezometer location were surveyed at each transplant site. For each wildling, an estimate of depth to groundwater from both the upper and lower piezometers was calculated and the average taken. In this manner estimates of depth to groundwater were calculated for each wildling at each monthly sampling date from June or July through October 1999, with the maximum depth among these sampling dates used for analysis.

Data Analysis

A three-factor, randomized, complete block analysis of variance (ANOVA; $\alpha = 0.05$) was used to detect differences among treatments for wildling survival, number of shoots per surviving wildling, and average shoot height using SAS (SAS Institute, Cary, NC, U.S.A.) (Littell et al. 1996). Wildling survival (out of eight wildlings), number of shoots per surviving wildling, and average shoot height were expressed on a per row basis. A similar three-factor, randomized, complete block ANOVA ($\alpha = 0.05$) incorporating a repeated-measures analysis based on year was used to detect differences among treatment means for aerial cover of sedges and other plant species. The Tukey-Kramer test ($\alpha = 0.05$) was used as a post-ANOVA comparison of differences between treatment means. Because of low survival for the fall transplant season (no wildlings survived in 13 of 42 rows), analyses of shoot number and average shoot height were performed only on data from the summer transplant season. All response variables satisfied ANOVA assumptions of normality and homogeneity of variances except shoot number, which required a transformation ($\ln[x + 1]$) to satisfy these assumptions. Variation in survival of wildlings transplanted into the greenhouse associated with species, season, and size was analyzed using logistic regression. Significant differences in greenhouse survival among species were interpreted using Bonferroni-adjusted pair-wise contrasts (adjusted $\alpha = 0.05$). Site physical characteristics were used to help interpret transplant performance.

Chi-square contingency analyses ($\alpha = 0.05$) (Ott 1993) were performed to test for significant relationships between individual wildling survival and depth to groundwater using SAS JMP software (SAS Institute). These analyses required data on the fate of individual wildlings, not the entire wildling rows. Separate analyses were conducted for each species ($n = 80$) to determine whether survival differed with maximum depth to groundwater during the 1999 growing season (June or July through October). Depths to groundwater were grouped into five categories for analysis: 1, groundwater no more than 7 cm below the soil surface; 2, 8–27 cm; 3, 28–47 cm; 4, 48–60 cm; 5, more than 60 cm. Data from fall transplants were not included in depth to groundwater analyses due to inaccessibility of most sites during the winter. Data from Hoxworth Springs sites 1 and 2 also were not included in depth to groundwater analyses due to the absence of groundwater tables at the depths measured at these sites (>1 m).

Results

Effects of Species, Season, and Size on Wildling Performance

Results of the effects of species, transplant season, and transplant size on wildling survival, number of shoots per surviving wildling, and average shoot height in the field are presented in Table 2. Wildling survival was slightly greater for *C. lanuginosa* than for the other species, although differences were only marginally significant ($F_{2,66} = 2.6$; $p = 0.0815$). Survival was higher during the summer versus fall season ($F_{1,66} = 46.4$; $p < 0.0001$) and for large versus small transplants ($F_{1,66} = 8.3$; $p = 0.0053$) for all species.

Analyses of shoots per surviving wildling and average shoot height were performed using only summer season data. Shoot numbers for summer transplants were significantly greater for large transplants ($F_{1,29} = 4.9$; $p = 0.0354$) and varied among species ($F_{2,29} = 9.5$; $p = 0.0007$). Mean shoot numbers were significantly greater for *C. lanuginosa* wildlings than for either *C. nebrascensis* or *C. rostrata* wildlings. Mean shoot height also was greater for large transplants ($F_{1,29} = 7.0$; $p = 0.0128$) and varied among species ($F_{2,29} = 34.1$; $p < 0.0001$). Mean shoot heights were greater for both *C. rostrata* and *C. lanuginosa* wildlings than *C. nebrascensis* wildlings.

Survival was greater in the greenhouse than in the field for each species, transplant season, and transplant size (Table 2), suggesting that mortality in the field was largely due to field conditions and did not result from transplanting stress or handling during lifting. Species and size trends were consistent between the greenhouse and field, although differences were significant only for species ($\chi^2_{2,67} = 11.71$; $p = 0.0029$). Field survival of *C. nebrascensis* relative to the other species was higher than that predicted by its

Table 2. Average values (means ± SE) for sedge wildling survival, number of shoots per surviving wildling, and shoot height in the field and survival in the greenhouse.

	Field			*Greenhouse*
Factor	*Survival* %	*Shoots* (n)	*Shoot Height* (cm)	*Survival* (%)
Species				
C. lanuginosa	46.9 ± 4.8	12.67 ± 1.73a*	31.1 ± 1.28a	95.8a
C. nebrascensis	35.3 ± 5.3	5.53 ± 0.90b	17.9 ± 1.02b	62.5b
C. rostrata	36.6 ± 5.2	7.87 ± 1.54b	34.9 ± 2.49a	91.7a
Season				
Summer	55.1 ± 3.5	Not tested	Not tested	77.8
Fall	24.1 ± 3.4			88.9
Size				
Large	46.1 ± 4.4	9.51 ± 0.95	30.3 ± 2.46	88.9
Small	33.0 ± 3.8	8.06 ± 1.62	25.7 ± 1.73	77.8

* Species followed by the same letter do not differ significantly according to three-factor randomized complete block ANOVA (Tukey honest significant difference, $\alpha = 0.05$) for the field and three-factor logistic regression analysis (Bonferroni-adjusted pairwise contrasts, adjusted $\alpha = 0.05$) for the greenhouse.

greenhouse survival rates, which were only about two-thirds as high as those of the other species.

Aerial cover (1999 and 2000) for the target sedge species and other plant species are presented by treatment in Table 3. Changes in mean aerial sedge cover after 1 year were small, although trends differed significantly among species ($F_{2,72} = 3.2$; $p = 0.0465$) and between seasons ($F_{1,72} = 9.0$; $p = 0.0065$). *Carex lanuginosa* and *C. rostrata* both showed slight increases in cover, whereas *C. nebrascensis* showed a slight decrease. Cover on summer transplant rows increased slightly, whereas cover on fall transplant rows decreased slightly. Additionally, few sedge seedlings established on control plots. Volunteer seedlings on control plots at most sites were dominated by *C. stipata* (owlfruit sedge), a species with densely clustered culms that produces many readily germinable seeds (Ewing 1996). Of the three species transplanted, a few seedlings of *C. nebrascensis* at Boggy Creek site 2 and Wildcat Creek site 2 constituted the only establishment on control plots.

Cover of other plant species increased dramatically between 1999 and 2000 for all treatments (Table 3). However, the relative amount of increase was similar among treatments except with respect to season, where the relative increase for summer transplant rows was significantly greater than for fall ($F_{1,72} = 14.7$; $p = 0.0003$). The vegetation was dominated by disturbance-associated species such as *Lepidium virginicum* (Virginia pepperweed), *Artemisia ludoviciana* (white sagebrush), *Polygonum lapathafolium* (curlytop knotweed), and *Erigeron divergens* (spreading fleabane) and by non-native grasses such as *Poa pratensis* and *Agrostis stolonifera* (creeping bentgrass). A few native wetland obligate graminoids, including *Juncus saximontanus* (Rocky Mountain rush) and *Eleocharis palustris* (common spikerush), also established, but their overall cover was low.

Relationships Between Wildling Survival and Site Factors

Properties of the upper 20 cm of soils in the transplant sites were highly variable among sites, with the exception of soil texture (Table 4). This variability probably reflects the diversity of environmental conditions and historical

Table 3. Average values (means ± SE) for percent aerial cover of transplanted sedge species and other plants in 1999 and 2000.

	Sedge Cover (%)		*Other Plant Cover (%)*	
Factor	*1999*	*2000*	*1999*	*2000*
Species				
C. lanuginosa	0.72 ± 0.05	1.41 ± 0.30	5.79 ± 1.17	29.80 ± 2.66
C. nebrascensis	0.90 ± 0.17	0.80 ± 0.17	7.90 ± 1.49	31.68 ± 2.36
C. rostrata	0.96 ± 0.09	1.49 ± 0.31	8.48 ± 2.17	28.12 ± 2.75
Season				
Summer	0.99 ± 0.07	1.77 ± 0.24	3.70 ± 1.31	20.20 ± 1.32
Fall	0.73 ± 0.04	0.70 ± 0.17	11.21 ± 1.49	39.53 ± 1.63
Size				
Large	0.97 ± 0.05	1.56 ± 0.22	6.80 ± 1.24	30.01 ± 2.17
Small	0.76 ± 0.06	0.91 ± 0.21	8.03 ± 1.74	29.72 ± 2.06
Control plots	0.21 ± 0.15	0.29 ± 0.15	10.00 ± 3.28	52.07 ± 5.89

Table 4. Physical properties of soils at sedge wildling transplanting sites.

Transplant Site	Soil Texture	Organic Matter n = 1 (%)	Bulk Density* Upper	Bulk Density* Lower
Boggy site 1	Loam	7.4	0.96 ± 0.08	0.95 ± 0.08
Boggy site 2	Clay loam	0.8	1.10 ± 0.02	1.07 ± 0.14
Hoxworth site 1	Clay loam	3.2	1.63 ± 0.16	1.71 ± 0.27
Hoxworth site 2	Loam	3.2	1.45 ± 0.03	1.54 ± 0.11
Lofer Cienega	Loam	6.1	0.68 ± 0.05	0.78 ± 0.06
Wildcat site 1	Loam	5.6	1.21 ± 0.07	1.25 ± 0.10
Wildcat site 2	Loam	4.7	1.13 ± 0.05	0.80 ± 0.07

* Values for bulk density are the mean (n = 3) ± standard error of the mean. Upper, upper portion of streambanks; Lower, lower portion of streambanks.

influences such as geology, meadow hydrology, and amount of time since meadow degradation.

Groundwater depths at individual sites fluctuated by as much as 85 cm during the sampling period, with variations of more than 50 cm typical on the upper portion of streambanks (Fig. 1). Groundwater depths were considerably greater (often by more than 35 cm) in 2000 than in 1999 across all sites for comparable time periods. The only exception occurred in October 2000, when groundwater levels rose dramatically in response to abundant early fall precipitation. Groundwater depths experienced by transplants (excluding those from the two Hoxworth Springs sites) at the time of transplanting ranged from −82 to +45 (i.e., standing water) cm (average, −18.5 cm) for summer transplants and −89 to +14 cm (average, −37.9 cm) for fall. Soil moisture exhibited a pattern similar to groundwater depth (Fig. 1). Soil moisture values for some 2000 measurement dates were less than one-half of values for comparable time periods in 1999, and similar to groundwater depths, soil moisture levels rose dramatically in October 2000.

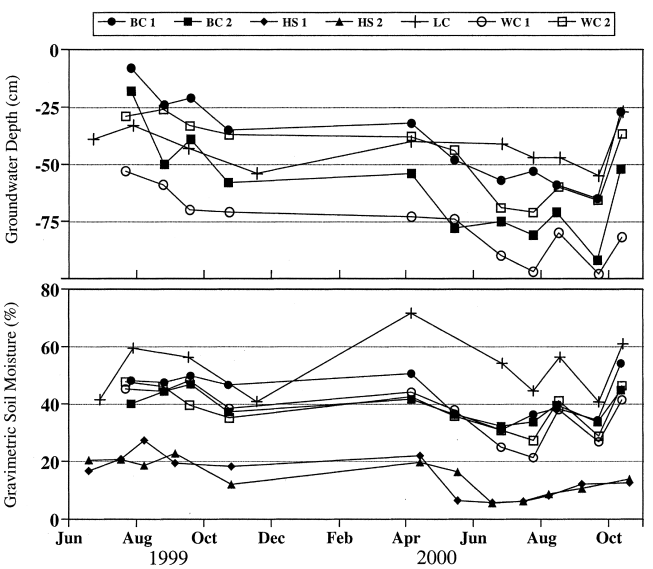

Figure 1. Groundwater depth and gravimetric soil moisture content for wildling transplanting sites during 1999 and 2000. Values for each site at each sampling date represent an average from the upper and lower streambanks (n = 2). Groundwater depth data are not displayed for Hoxworth Springs sites 1 and 2 because of absence of groundwater at the depths measured at these sites (>1 m). BC, Boggy Creek; HS, Hoxworth Springs; LC, Lofer Cienega; WC, Wildcat Creek.

Near-record July–September precipitation in 1999 (particularly in eastern Arizona) coupled with abnormally low precipitation during late 1999 and most of 2000 account for these patterns in groundwater depth and soil moisture. Above-bankfull flows inundated lower streambanks on Boggy and Wildcat Creek sites in August 1999 (personal observation), resulting in the loss of a few wildlings through scouring. In contrast, because of low precipitation during the first half of the year, streamflow was absent on some sites for several months during 2000.

The results of chi-square contingency analysis indicated significant associations between survival of summer transplants and maximum groundwater depth during the first 4 months after transplanting (June or July through October 1999) for each species (*C. lanuginosa* $\chi^2_{4,75} = 16.9$, $p = 0.0020$; *C. nebrascensis* $\chi^2_{4,75} = 20.5$, $p = 0.0004$; *C. rostrata* $\chi^2_{4,75} = 12.9$, $p = 0.0207$) (Table 5). *Carex lanuginosa* wildling survival was relatively high across a range of groundwater depths (−28 to −60 cm). In contrast, high survival of *C. nebrascensis* and *C. rostrata* was restricted to areas where the maximum groundwater depths were from −28 to −47 cm (88.2%) and −8 to −27 cm (64.3%), respectively. Survival was poor for all species where maximum groundwater depth was −7 cm or less.

Discussion

Comparison Among Species, Seasons, and Transplant Sizes

Relatively similar field survival rates were observed among the three species, possibly because they all have a highly rhizomatous growth habit and similar phenology (Hermann 1970; Hurd et al. 1992). The results of this and other studies (Allen-Diaz 1991; Sala & Nowak 1997; Steed 2001) suggest that these species differ in terms of optimal

Table 5. Percentage survival of summer transplants of *Carex lanuginosa*, *C. nebrascensis*, and *C. rostrata* ($n = 80$ for each species) in different maximum groundwater depth categories.

	Maximum Groundwater Depth				
Species	*No more than −7 cm*	*−8 to −27 cm*	*−28 to −47 cm*	*−48 to −60 cm*	*More than −60 cm*
C. lanuginosa	11.1	33.3	76.5	78.6	59.1
C. nebrascensis	7.3	55.6	88.2	66.7	50.0
C. rostrata	8.3	64.3	50.0	60.0	31.6

groundwater depths. Nevertheless, they often occur in intermixed stands, indicating that they have similar environmental requirements. The lower greenhouse survival of *C. nebrascensis* relative to the other species suggests that its tolerance for the initial stress of transplanting may be lower.

Differences in shoot numbers and shoot heights among the species probably reflect inherent differences in root and shoot morphology and clonal architecture and not differences in performance. Naturally occurring clones of *C. lanuginosa* are characterized by small-diameter moderately tall shoots and high shoot densities, *C. nebrascensis* by large-diameter moderately tall shoots and moderate shoot densities, and *C. rostrata* by large-diameter relatively taller shoots and moderate shoot densities (Steed, unpublished data; Hermann 1970). However, greater shoot numbers and heights for large versus small size transplants of all species suggests the large size transplants were more vigorous.

One year was insufficient to observe substantial increases in sedge cover within transplant rows due to rhizomatous growth and expansion. Regardless of treatment, closer spacing than 0.5 m would be required to obtain closure between transplants within 1 or 2 years. Although small, the greater increases in cover among rows of summer transplants and large transplants are in agreement with season and size trends for survival, shoot numbers, and shoot heights. Despite large increases in cover of disturbance-associated plant species in the year after restoration activities, observations made during field visits suggested that these plants did not attain heights sufficient to shade sedge transplants. However, it is likely that transplant growth was reduced by competition with these invading plants, particularly where groundwater tables were deep and available soil moisture was low (Budelsky & Galatowitsch 2000; Martin & Chambers 2001).

Seasonal differences in plant phenological status and establishment conditions at transplant sites may account for dissimilar survival rates between summer and fall transplants. Belowground nutrient and carbohydrate levels in sedges are low in early summer due to high demand by aboveground tissues for growth and flower or seed production and are gradually replenished during summer and early fall (Bernard & Solsky 1977; Roseff & Bernard 1979; Auclair 1982; Steele et al. 1984). However, lower belowground reserves of summer transplants may have been offset by above- and belowground plant growth that replenished these reserves and resulted in root contact with groundwater (or development of extensive root systems in response to anaerobic conditions). In contrast, fall transplants had limited (although initially larger) carbohydrate, nutrient, and water reserves on which to survive the winter before initiating new growth in spring. Fall greenhouse transplants, which were able to immediately initiate growth, had high survival (88.9%). Yetka and Galatowitsch (1999) suggested that inadequate underground reserves were a primary factor responsible for low survival rates among *Carex lacustris* (hairy sedge) and *C. stricta* (upright sedge) rhizomes transplanted in fall. Higher survival during the fall season by large transplants in the present study suggests transplanting larger amounts of material could enhance the survival of fall transplants by providing them with larger reserves.

Access to groundwater and surface soil moisture also may have contributed to survival differences among seasons. Average groundwater depth for summer transplants was less (−18.5 cm) than for fall (−37.9 cm). Because transplant roots were approximately 15 cm below the soil surface, groundwater was likely more accessible for summer transplants, and this may have resulted in lower water stress despite greater transpiration demands. Surface soil moisture levels were also generally higher during summer than fall.

Observations of transplant mortality during site visits in April 2000 suggested that frost heaving also contributed to differential survival among the seasons. Some fall transplants had been partially or completely lifted out of the unconsolidated soils present at several sites, leaving them exposed to desiccation. Frost heaving caused greater mortality among fall transplants because they were unable to extend roots into the surrounding soil before winter.

Small transplants had more limited root systems and carbohydrate and water reserves and presumably had lower root/shoot ratios than large transplants, probably contributing to greater mortality under stressful conditions. Peri et al. (1982) concluded that the greater capacity of the root systems of larger mature *Carex barbarae* (Santa Barbara sedge) plants to store nutrients and water was an important factor in higher transplant survival of mature plants compared with smaller young plants.

Depth to Groundwater and Survival

Groundwater depth was a key determinant of wildling survival in this study—survival was reduced under both very shallow and deep groundwater tables. Poor survival of transplants where groundwater tables were very shallow was surprising because naturally occurring established stands flourish under these same conditions at nearby meadows (Steed 2001). However, young shoots in established sedge stands receive substantial support via the transfer of carbohydrates, nutrients, water, and oxygen through rhizomes of the parent plant (Fagerstedt 1992; de Kroon et al. 1998; D'Hertefeldt & Jonsdottir 1999). Support from the parent plant permits establishment under stressful conditions, such as waterlogged or dry soils, and is an important advantage of vegetative reproduction (Grime 1979). Moreover, shoot initiation in established stands can be timed to coincide with favorable conditions. Transplants, however, must establish root and shoot systems with limited water, nutrient, and carbohydrate reserves during time periods that may not be conducive to establishment.

Transplants planted within stream channels were often completely submerged. Submersion was probably more detrimental to fall transplants, because they were unable to extend shoots above the water surface. Contact of leaves with air is crucial for the avoidance of root anoxia in many wetlands plants such as sedges (Armstrong et al. 1994). Shoot submersion also left wildlings vulnerable to shading by algal blooms that developed at some sites shortly after summer transplanting. Comes and McCreary (1986) noted that algal blooms were an important cause of sedge transplant mortality along the shorelines of a reservoir in the Pacific Northwest. In the present study, survival of wildlings transplanted within stream channels likely could have been increased if pruned shoots had been left tall enough to allow aerial contact and the extension of shoots above algae. Seibert (1968) recommended that reed and sedge transplants be submerged no more than two-thirds of their height.

With greater groundwater depth (more than −60 cm), it is likely that many transplants failed to establish contact with moist soils or groundwater before desiccation. As was the case for shallow groundwater tables, transplants may be more sensitive to greater groundwater depth than established sedge stands, which are known to endure large seasonal depressions of groundwater tables (Sala & Nowak 1997; Svejcar & Riegel 1998). Mortality due to water stress in the present study was greatest in the first months after transplanting. Only slight additional mortality was observed among established wildlings when groundwater tables dropped during summer 2000.

Variation in survival among species in response to differing groundwater depths emphasizes the importance of matching species to site conditions. Relatively high survival by *C. rostrata* (64.3%) where groundwater tables were fairly shallow (−8 to −27 cm) is in agreement with observations of its tolerance for saturated anaerobic soils (Hansen et al. 1995; Law et al. 2000; Steed 2001). However, similar survival of *C. lanuginosa* (65%) and *C. nebrascensis* (50%) where groundwater depth was greatest (more than −60 cm) was unexpected because previous studies suggested the former species is less tolerant of deep water tables (Allen-Diaz 1991; Sala & Nowak 1997). Despite the shoots of all transplants being pruned to 15 cm, root-to-shoot ratios of *C. lanuginosa* transplants may have been initially greater than those of *C. nebrascensis* because of the smaller leaf area per shoot for the narrower leafed *C. lanuginosa* (observations made during transplanting suggested similar initial root areas between the species). Therefore, *C. lanuginosa* root systems may have been better able to keep up with transpiration demands during the initial weeks after transplanting.

Precipitation patterns in the southwestern United States differ from those of other regions where sedge transplanting trials have been carried out. In contrast to many regions of the United States, southwestern riparian meadows typically receive abundant precipitation in late summer, meadow groundwater tables are often recharged at these times, and these conditions should enhance the survival of summer transplants in the southwest. Results may have been different if summer precipitation in 1999 had not been as abundant, as was the case in 2000.

Other Site Characteristics and Survival

The properties of soils at transplanting sites indicate that conditions for plant establishment were more stressful than at eight nearby intact meadows that had not suffered degradation (Steed, unpublished data). Soil bulk densities were above 0.65 on all transplant sites, whereas bulk densities on the intact meadows averaged 0.52, with 0.65 exceeded on only one of the eight sites. High bulk densities hinder rhizome and root growth in many herbaceous species due to poor soil aeration and high mechanical impedance (Landhausser et al. 1996). Organic matter also tended to be lower on transplant sites than on intact meadows. Higher organic matter often equates to higher nutrient availability, higher water storage capacity, and lower mechanical impedance (Landhausser et al. 1996; van der Valk et al. 1999).

Conclusions and Recommendations

Our results suggest that successful establishment of sedges in southwestern U.S. riparian meadows can be increased if transplanting occurs during summer with larger transplants and species are matched with appropriate depths to groundwater. Survival rates for the summer season of 79%, 88%, and 64% for *C. lanuginosa*, *C. nebrascensis*, and *C. rostrata*, respectively, were obtained when species were transplanted at appropriate depths to groundwater. Moreover, these survival results were achieved using relatively small amounts of transplant material. Sources of sedge transplant material are limited, and care must be taken to ensure lifting wildlings does not harm intact ripar-

ian meadows. Although using a larger transplant size resulted in modestly higher survival, shoot numbers, and average shoot height, the size and status of source populations and conditions at planting sites should also be considered in selecting an appropriate transplant size. Larger transplant sizes may be more appropriate under highly stressful establishment conditions. Additionally, transplant shoots should be maintained at heights sufficient to protrude above surface water (if present) to help prevent anoxia or pruned to increase root-to-shoot ratios where conditions are dry.

When selecting species for revegetation, restoration practitioners also should consider factors such as plant attributes or restoration goals. For example, the superior soil binding properties of *C. nebrascensis* roots (Manning et al. 1989; Kleinfelder et al. 1992), coupled with its tolerance for intense herbivory (Ratliff & Westfall 1992; Hansen et al. 1995), make it especially suited for many restoration situations.

Summer transplanting during the current study was timed to occur at the end of the early summer drought period and before the onset of summer rains, which occurred on the typical schedule (early July) during 1999. Because the timing of these summer rains can vary from year to year, delaying transplanting until they have begun may be wise. Discretion should be used in applying these results to regions other than the southwestern United States, because the climate, geology, and genetic makeup of plants in these areas might favor different transplanting seasons and groundwater depths.

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