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Effects of soil type, rainfall, straw mulch, and fertilizer on semi-arid vegetation establishment, growth and diversity

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ABSTRACT

Revegetation in arid and semi-arid environments often involves strategies to augment soil properties to promote plant establishment and growth while ameliorating the effects of variable rainfall. A southern Arizona USA greenhouse experiment evaluated the impact of rainfall, common amendments, and three soil types on grassland revegetation. Based on rainfall data from a nearby semi-arid site, three irrigation levels were used to simulate the rainfall of a dry (275 mm), average (320 mm), and wet (555 mm) year. The three amendments were bare soil, straw (4.5 Mg/ha with a tackifier), and straw plus slow-release fertilizer (7–2–3 NPK, 3.4 Mg/ha). Three field-collected soil types were used: a very gravelly sand, a very gravelly loamy sand, and a gravelly sandy loam. Four seed mixes were used as a blocking factor. There was a significant interaction between amendment and soil type, soil type and rainfall scenario, as well as amendment and rainfall scenario. Straw alone or with fertilizer increased aboveground biomass (72–177% increase) on the gravelly sandy loam, and very gravelly loamy sand soils but decreased biomass on the very gravely sand (13% and 54%). Straw with fertilizer did not change species richness and diversity significantly, but it resulted in a greater than 50% decline in establishment for all soil types. Straw alone significantly increased the aboveground biomass only in low (205%) and average rainfall scenarios (40%), but not when rainfall was high (11%). The specific site conditions ultimately determine which practices will result in successful revegetation.

1. Introduction

Establishing vegetation for mineland reclamation in semi-arid areas can be challenging because rainfall is unpredictable and scarce but also because reclaimed soils have variable capacity to retain moisture and nutrients (Thomas and Squires, 1991). Soil texture and structure impact the infiltration and retention of moisture and play an important role in revegetation (Noy-Meir, 1973). The amount of rainfall needs to be sufficient for germination but for successful establishment, soil moisture must be retained long enough so that, after germination, root development and elongation stay ahead of the drying front (Roundy et al., 1997) and the speed of the drying front is controlled by soil properties. The soils on heavily disturbed lands, such as mine tailings dams, waste rock piles or road cuts may come from several to many meters below the surface instead of being surface soil. Although the deep material is often mixed with or capped with small amounts of saved soil (e.g. Wood and Buchanan, 2000), the resulting constructed soil can be one with a substantially different responses compared to reclamation practice recommendations appropriate in the less-disturbed surroundings (Heneghan et al., 2008). Reclamation projects have commonly used soil amendments as a strategy to conserve soil moisture and to ameliorate suboptimal microclimatic conditions at the soil surface in order to increase vegetation germination, establishment, and growth (e.g. Whisenant, 1999).

Straw and other kinds of mulch have been common temporary solutions to the problem of poor soil and in many places are required best practices (Wood and Buchanan, 2000). Straw mulch cover has been shown to reduce runoff, increase infiltration, dampen extreme soil surface temperatures, and decrease evaporation (Maurya and Lal, 1981; Chambers, 2000; Ji and Unger, 2001; Ghosh et al., 2006). As a result of these effects, mulch can increase plant biomass production, growth rate, and root elongation (Chambers, 2000; Rahman et al., 2005; Ghosh et al., 2006). Mulch effects on soil moisture are variable and interact with soil texture, rainfall amount and frequency, as well as evaporative demand (Jalota and Prihar, 1998). Even when mulch enhances soil absorption and retention of moisture, the effects of mulch on plant growth and establishment are mixed (Whisenant, 1999) and not all species benefit from mulch application at least in terms of establishment and survivorship (Wilson et al., 2004; Dostalek et al., 2007). Absent a requirement for mulch to control erosion, the

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decision to apply it on semi-arid areas is complicated because in low rainfall years mulch is expected to have little effect because there is too little moisture for seedlings to establish (e.g. Roundy et al., 1997). In high rainfall years, plants may have enough moisture to grow with or without the mulch. Cost of mulch must be balanced against the probability of getting amounts of rain where it will make a difference to plant growth and establishment.

In addition to applying straw mulch, fertilizer is often used in revegetation projects to ameliorate the poor soil fertility caused by disturbance and the use of sterile subsurface materials as soils (Rodgers and Anderson, 1995; Leiros et al., 1996; Eastham et al., 2006). While fertilization has met with success in some situations (McGeehan, 2009), more commonly it has been found that fertilization promotes invasive species over natives, which tend to be adapted to limited soil nutrients (Gendron and Wilson, 2007). Occasional negative effects of fertilizer application on plant growth in drought have been reported as well (Chapin, 1980).

Though the individual effects of straw mulch, rainfall, fertilizer, and soil texture have been studied, the interaction among them on plant establishment, growth and diversity are much less documented. This study was designed to determine the effect of adding straw mulch and mulch with fertilizer on the establishment, biomass production, species richness and diversity of native species growing in three incrementally coarser soils. The study also evaluated how these effects change in a wet, average and dry year.

2. Materials and methods

2.1. Experimental design

The experiment took place in two greenhouses at the University of Arizona Campus Agricultural Center, Tucson, Arizona, USA. Environmental conditions were intended to approximate a proposed mine reclamation site (the target site) 80 km southeast of Tucson (31°51.447N, 110°46.046W; 1500 m elevation). The greenhouse daytime temperatures were limited to maximum of 35 °C ± 2° consistent with the average summer temperature of the target site, but temperature was not controlled at night. The experimental design was a randomized complete block design with three rainfall scenarios, three amendment levels, and three soil types. Blocking factors included four randomly assigned seed mixes and two greenhouses with two blocks each. There were four replications of every unique treatment combination for a total of 432 15-l pots.

Simulated rainfall applications for dry, average, and wet years were developed from the target site data. The daily rainfall data from 1976 to 2006 (SRER, 2007) from two rain gauges that had similar elevation and were less than 10 miles away from the target site was used. We ranked the annual rainfall amounts from low to high (229 mm to 736 mm). The years near the 10th, 50th and 90th percentile were inspected for those that had sufficient frequency and intensity rainfall to allow plant growth. The 12th-percentile (285 mm) was selected as the example dry year, 48th-percentile (398 mm) as the example average year, and 90th-percentile (532 mm) as the example wet year. The simulated rainfall schedule reproduced the target site's bimodal annual precipitation pattern such that approximately 60% of the selected annual amounts were applied from 28 August to 29 November 2007, and 40% from 4 February to 3 May 2008 (Table 1). No simulated rainfall took place between the two application periods in order to mimic the normal dry period between the monsoon and winter rains. Simulated rainfall was spaced over a 3-day interval in summer and 3- to 6-day intervals in winter to imitate the local intermittent rainfall pattern. Despite pressure compensating down-spray emitters and frequent calibration, the amount of water given to each pot within a treatment may have varied by up to 6% due to variable pressure in the irrigation system. Variation in simulated rainfall was evaluated through testing a random selection of three down-spray emitters that were near to, midway from, and at the far-end from the water supply pipe along each branch line. This was repeated three times and, the first two times, the water pressure was adjusted to minimize differences among emitters. The final measurement was used to calculate the range of difference in the amount of water emitted. Based on the flow rate testing, the difference among emitters within a treatment did not cause overlap among the simulated rainfall treatments.

Table 1
Irrigation schedule for the low, average, and high rainfall scenarios.

Day count	Simulated rainfall amount (mm)					
	Summer			Winter		
	Low	Average	High	Low	Average	High
1			15	5	5	5
2		15	15			
3	10	15	15			
4	10	15	15		3	3
5						
6						
7	5	8	11	5	5	5
8						
9						
10	5	8	11			3
11						
12						
13				5	5	5

The schedule followed these regular intervals for 94 days (summer) and 90 days (winter).

The three amendment levels were bare soil, straw adhered to the soil with a tackifier (tackified straw), and tackified straw plus slow-release organic fertilizer. Tackified straw consists of sterilized straw applied a rate of 4.5 Mg/ha (2 tons/acre) and then sprayed with a copolymer acrylamide (Envirotac II, Environmental Products & Applications, Inc., Palm Desert, California) diluted to a rate of 11 kl/ha, which adheres the straw together and to the soil surface. This matched the expected practices at the target site to prevent wind from relocating the straw. For the fertilizer treatment, a slow-release pelletized fertilizer (7–2–3 NPK, Biosol Organic Fertilizers, Denver, Colorado) was evenly spread across the soil surface at a rate of 3.4 Mg/ha before the straw and tackifier were applied.

Each of three common parent materials expected to be reclaimed at the target site were mechanically excavated to a depth of 2–3 m and sieved through a 5 cm × 5 cm screen to remove large rock fragments. During this process, surface soil was mixed with material from greater depth to simulate expected reclamation conditions. A very gravelly sand (VGS soil) was derived from a sedimentary rock mix of siltstone, sandstones and conglomerates from the Willow Canyon Formation. A very gravelly loamy sand (GLS soil) was derived from a conglomerate limestone parent material. A gravelly sandy loam (SL soil) was derived from a conglomerate from a late tertiary alluvium. Soils were analyzed for particle size, NPK, organic matter, pH, cation exchange capacity, and base saturation (Table 2).

Four seed mixes were included as a blocking factor to make the results more broadly applicable and less dependent on single species responses. Twenty-eight native species were allocated into four overlapping seed mixes (10–11 species each; Table 3) with similar functional group composition to the semi-desert grassland target site: warm-season perennial grasses (82% of each mix by number of seeds), cool-season perennial grasses (2%), annual

Table 2
Particle size composition, N–P–K and organic matter content, pH, cation exchange capacity (CEC) and base saturation for the three soil types.

	VGS	GLS	SL
Texture classification	Very gravelly sand	Very gravelly loamy sand	Gravelly sandy loam
Gravel (%)	81	57	43
Sand (%)	88	76	68
Silt (%)	8	18	18
Clay (%)	4	6	14
NO_3 (ppm)	1	2	2
PO_4 (ppm)	4	3	6
K (ppm)	64	136	65
Organic matter (%)	0.9	3.1	1.7
pH	7.1	8.2	8.4
CEC (meq/100 g)	13.7	26.1	29.9
Base saturation (%)	99.5	99.9	99.8

Table 3
Species and functional allocation in the four seed mixes.

		FG	Nutrient need	Seed allocation (%)			
				Mix 1	Mix 2	Mix 3	Mix 4
Mexican gold poppy	*Eschscholzia californica ssp. mexicana*	*AF*	Low		7		8
Orange caltrop	*Kallstroemia grandiflora*	*AF*	n/a			7	
Big purple tansyaster	*Machaeranthera tanacetifolia*	*AF*	Low	7			
Sixweeks needle grama	*Bouteloua aristidoides*	*AG*	n/a	4	4	4	4
Bottlebrush squirreltail	*Elymus elymoides*	*CSPG*	Low	2			
Prairie Junegrass	*Koeleria macrantha*	*CSPG*	Medium			2	
Muttongrass	*Poa fendleriana*	*CSPG*	Low			2	
Desert marigold	*Baileya multiradiata*	*PF*	n/a	3			2
Desert senna	*Senna covesii*	*PF*	n/a		3		2
Desert globemallow	*Sphaeralcea ambigua*	*PF*	Low				2
Gooseberryleaf globemallow	*Sphaeralcea grossulariifolia*	PF	Low			3	
Whitethorn acacia	*Acacia constricta*	*SH*	Low	2			2
Catclaw acacia	*Acacia greggii*	*SH*	Low			1	
Fourwing saltbush	*Atriplex canescens*	*SH*	Low			1	
False mesquite	*Calliandra eriophylla*	*SH*	Low		2		
Whitestem paperflower	*Psilostrophe cooperi*	*SH*	n/a		2		
Skunkbush sumac	*Rhus trilobata*	*SH*	Low	2			
Red threeawn	*Aristida purpurea var. longiseta*	*WSPG*	Low			20	20
Cane beardgrass	*Bothriochloa barbinodis*	*WSPG*	Medium		16	20	
Sideoats grama	*Bouteloua curtipendula*	*WSPG*	Medium	16	16		20
Blue grama	*Bouteloua gracilis*	*WSPG*	Low	16	16		
ROTHROCK grama	*Bouteloua rothrockii*	*WSPG*	n/a	16			20
Arizona cottontop	*Digitaria californica*	*WSPG*	High		16	20	
Plains lovegrass	*Eragrostis intermedia*	*WSPG*	Medium		2		
Tanglehead	*Heteropogon contortus*	*WSPG*	Low		16		
Curly mesquite	*Hilaria belangeri*	*WSPG*	Low			20	
Green sprangletop	*Leptochloa dubia*	*WSPG*	Medium	16			
Sand dropseed	*Sporobolus cryptandrus*	*WSPG*	Low	16			20

Each seed mix totaled to 100%. FG = functional group; WSPG = warm-season perennial grass; CSPG = cool-season perennial grass; AG = annual grass; PF = perennial forb; AF = annual forb; SH = shrub.

grasses (4%), perennial forbs (3%), annual forbs (7%), and shrubs (2%) based on the Ecological Site Descriptions for the site (NRCS, 2007). The 28 species were split between the four mixes as evenly as possible while balancing the functional groups. Then, the species most commonly found at the target site were used to complete the mixes while keeping each mix as unique as possible. All seeds used came from a large-scale commercial seed vendor and were manually sorted to be visually intact. Each pot was hand sowed with 100 seeds onto bare soil before the amendment treatments were applied. The number of plants established was tallied 3–4 weeks after the beginning of each simulated season and 2–4 weeks after the end of each simulated season. All biomass was then harvested to 1 cm above the soil surface, separated by species, oven-dried (70° C for 48 h), and weighed. Any plants that sprouted from the soil seedbank were removed as soon as they could be identified and not used in the analysis.

Table 4
MANOVA results for the combined response variables: aboveground biomass, percent establishment, species richness, and Shannon's index of diversity. Blocking factors – blocks, seed mixes, and seed mix interactions – are omitted from the table.

MANOVA			
Experimental factors	Pillai–Bartlett statistic	Approx. *F* value	*p*
Soil type	0.70	46.38	<0.001
Rainfall	0.60	40.50	<0.001
Amendment	0.63	42.88	<0.001
Soil type × amendment	0.38	9.91	<0.001
Soil type × rainfall	0.34	8.89	<0.001
Rainfall × amendment	0.17	4.15	<0.001

Table 5
Univariate ANOVA results for aboveground biomass, establishment percentage, species richness, and Shannon's index of diversity. Blocking factors, blocks, seed mixes, and seed mix interactions, are omitted from the table.

Experimental factors	df	Aboveground biomass		Establishment (%)		Species richness		Shannon's index of diversity	
		F value	*p*	*F* value	*p*	*F* value	*p*	*F* value	*p*
Soil type	2	272.45	<0.001	131.34	<0.001	108.86	<0.001	78.89	<0.001
Rainfall	2	167.95	<0.001	181.41	<0.001	95.69	<0.001	58.10	<0.001
Amendment	2	39.92	<0.001	140.08	<0.001	61.34	<0.001	29.20	<0.001
Soil type × amendment	4	32.54	<0.001	4.22	0.002	17.87	<0.001	13.62	<0.001
Soil type × rainfall	4	23.03	<0.001	29.71	<0.001	10.22	<0.001	5.54	<0.001
Rainfall × amendment	4	3.73	0.005	10.51	<0.001	0.90	0.521	0.27	0.900
	379								

2.2. Statistical analysis

The dependent variables were: aboveground biomass, establishment percentage, species richness, and Shannon's index of diversity. The establishment count data were used to determine species richness and Shannon's index of diversity. Transformations were done to normalize the distributions of biomass, and Shannon's index data (square-root and squared, respectively). We used R 2.14.2 (R, 2012) to perform a MANOVA and subsequent univariate ANOVA tests for the main effects and two-way interactions between the independent variables. We visually inspected the residual plots and used a Kolmogorov–Smirnov goodness-of-fit test to verify that the residuals were distributed normally. The greenhouse blocking factor was only additive but the seed mix factor was included with the two-way interactions. Tukey's HSD test was performed to detect significant differences ($p < 0.05$) among group least square means of the univariate analyses. Ten pots were excluded from the analysis due to apparent errors in pot treatment allocation, data or sample collection, or subsequent data-handling, resulting in a final sample size of 422 pots.

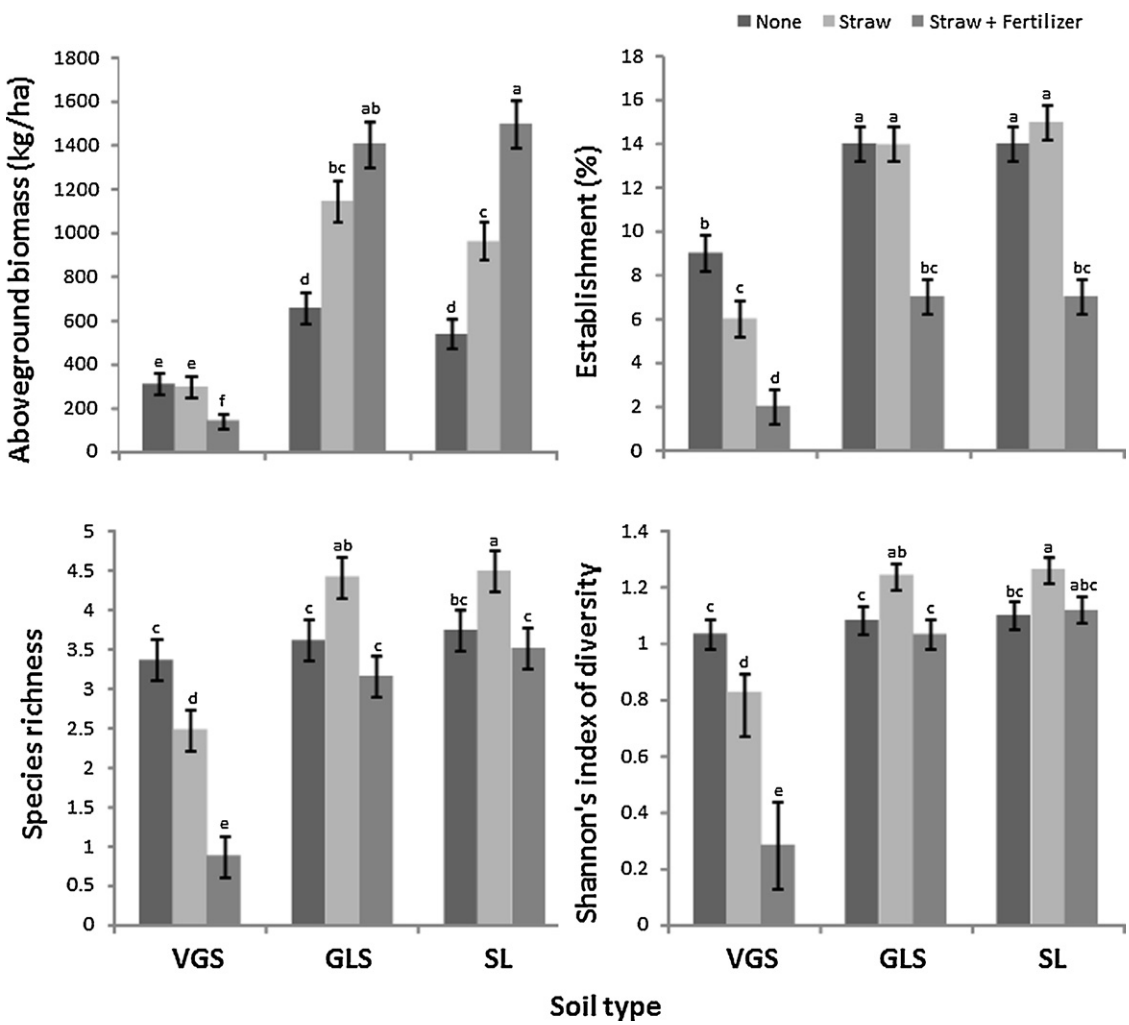

Fig. 1. Interactive effects of soil type (VGS = very gravelly sand, GLS = very gravelly loamy sand, SL = gravelly sandy loam) and amendment on aboveground biomass, establishment, species richness, and diversity. Significant difference at $p < 0.05$ is noted by different letters above each bar, based on Tukey HSD tests. The graphed values are the actual values for richness and establishment and the back-transformed values for biomass and diversity.

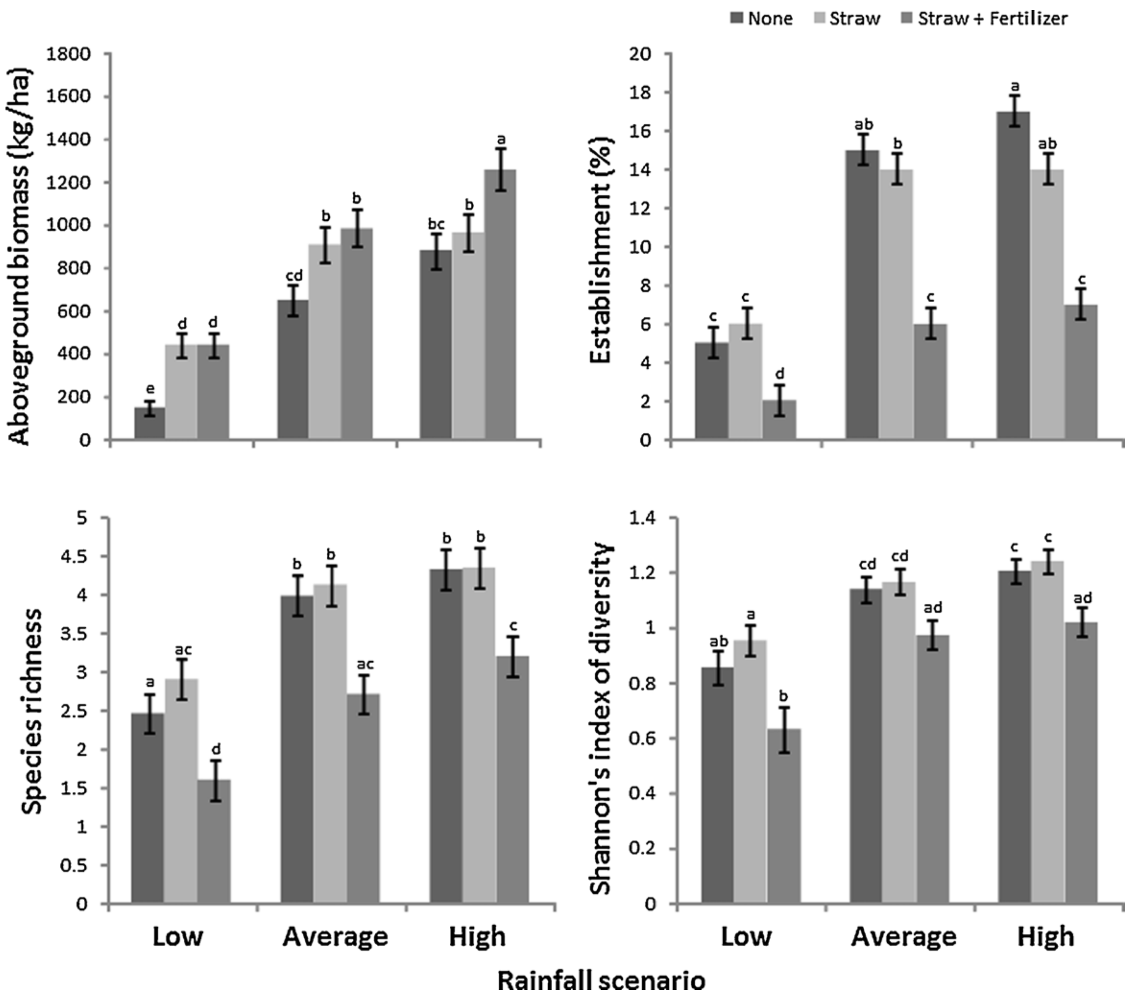

Fig. 2. Interactive effects of rainfall scenario (low = 275 mm, average = 320 mm, high = 555 mm) and amendment on aboveground biomass, establishment species richness, and Shannon's index of diversity. Significant difference at $p < 0.05$ is noted by different letters above each bar, based on Tukey HSD tests. The graphed values are the actual values for richness and establishment and the back-transformed values for biomass and diversity.

3. Results

Based on the MANOVA analysis, all second order interactions among amendments, rainfall scenario and soil were significant ($p < 0.001$; Table 4).

The amendment and soil type interaction was also significant ($p < 0.005$) in the univariate ANOVAs for all of the dependent variables (Table 5). Straw mulch, whether by itself or with fertilizer, resulted in a favorable response on the GLS and SL soils to increase aboveground biomass (177–72% increase) compared to bare soil, but biomass responded negatively with VGS soil when fertilizer was applied (54% decrease) and neutrally without fertilizer (Fig. 1) again compared to bare soil. For GLS and SL soils, addition of straw mulch without fertilizer resulted in generally higher species richness and diversity compared to bare soil or straw with fertilizer, but did not improve establishment significantly (Fig. 1). Adding fertilizer to the straw resulted in no significant improvement in species richness and diversity and the lowest establishment percentage for all soil types (Fig. 1). In general, VGS showed a negative response to straw addition, with or without fertilizer compared to bare soil, for all metrics except for aboveground biomass (Fig. 1) where straw resulted in no difference.

The significant interaction between amendment and rainfall appears largely driven by the aboveground biomass and species establishment variables ($p = 0.006$ and <0.001 respectively, Table 5) while species richness and Shannon's index responded similarly to amendments, regardless of changes in water addition. Straw by itself only significantly increased the aboveground biomass in dry (205%) and average rainfall scenarios (40%), and it had little effect on the biomass when rainfall was high (Fig. 2). Adding organic fertilizer to the straw significantly augmented the biomass production compared to unfertilized treatments regardless of the rainfall scenarios (217% increase in low, 52% in average and 48% in high, Fig. 2). Straw mulch alone did not change establishment significantly in any scenario (Fig. 2). Combining organic fertilizer with straw reduced the establishment significantly under all rainfall scenarios (54% decrease in low, 60% in average and 55% in high, Fig. 2) compared to the other amendment treatments.

The interaction between soil type and rainfall is best demonstrated by the GLS and SL soils biomass production increase (189% and 238%) when going from the low to average scenario rainfall (Fig. 3) but lacking significant response going from average to high rainfall (23% and 17%). The VGS soil lacked a significant response to all rainfall scenarios (19% increase from low to average and 42% from average to high rainfall scenarios; Fig. 3). This pattern was repeated for establishment, species richness, and diversity (Fig. 3) with little response from VGS soil and between low and average simulated rainfall but without substantial increase when comparing average to high simulated rainfall.

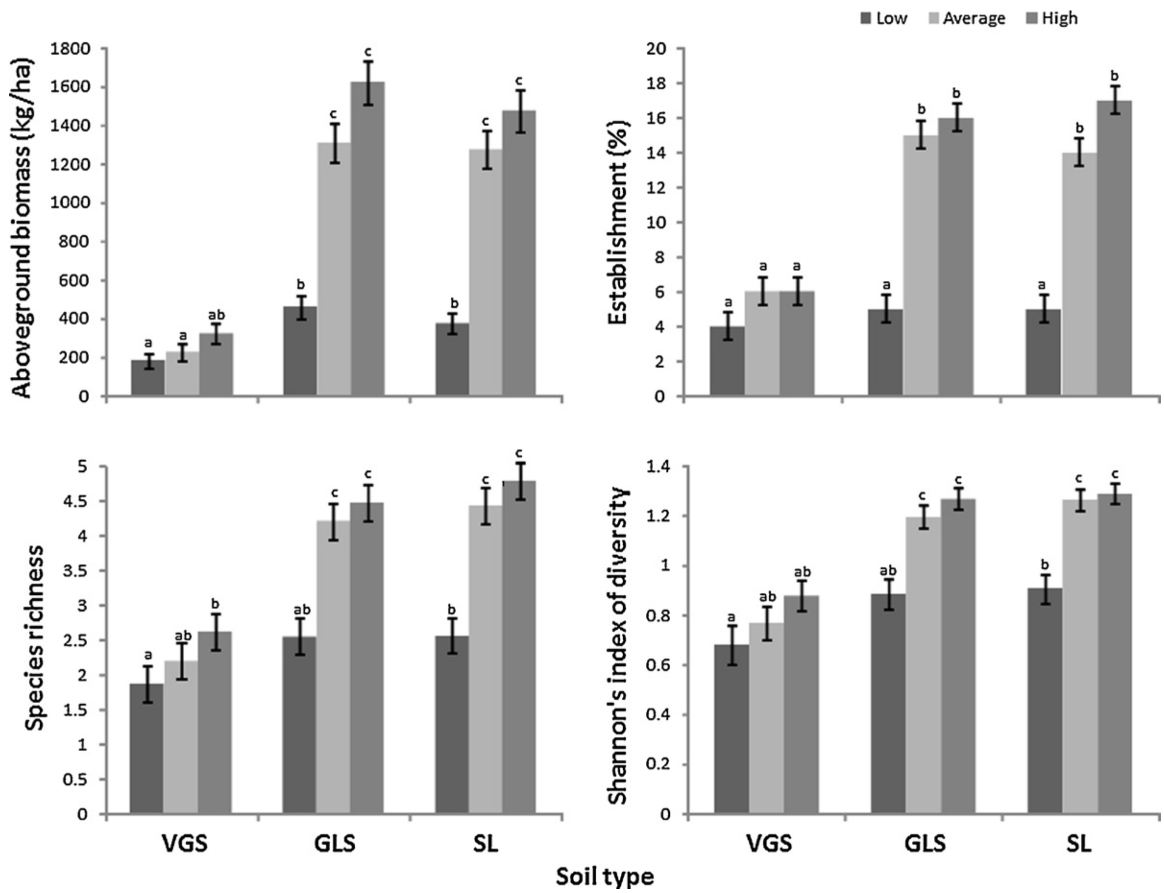

Fig. 3. Interactive effects of soil type (VGS = very gravelly sand, GLS = very gravelly loamy sand, SL = gravelly sandy loam) and rainfall scenario (low = 275 mm, average = 320 mm, high = 555 mm) on aboveground biomass, establishment, species richness, and diversity. Significant difference at $p < 0.05$ is noted by different letters above each bar, based on Tukey HSD tests. The graphed values are the actual values for richness and establishment and the back-transformed values for biomass and diversity.

4. Discussion

Reclamation influences range from straw and fertilizer which are easily applied or withheld, through soil texture which is possibly influenced if soil is moved as part of the project, to rainfall which can only be observed. Vegetative correlates of reclamation success were assessed in this paper as the result of differences in of soil texture, addition of straw and fertilizer, as well as contrasting rainfall scenarios.

The results of the different soil textures are better described as a threshold response rather than an incremental or gradient response to decreasing soil coarseness. The GLS and SL soils grouped together with similar responses to the treatment variables while the VGS soil either had no response or an opposite response compared to the others. It is possible that sufficient fine material occurred in the GLS and SL soils (a very gravelly loamy sand and a gravelly sandy loam) to support revegetation compared to the VGS soil (a very gravely sand; Table 2).

The application of straw had a positive impact on GLS and SL soils with increased biomass, richness and diversity when there was average or greater rainfall. This is a consistent with other studies showing beneficial effects of mulch addition. Gebremeskel and Pieterse (2008) found that mulch significantly improved the dry matter yield of seeded species (6–20 times more than controls) on a silty clay loam soil in Ethiopia. Chambers (2000) found increased seedling establishment and seed retention in mulched plot compared to bare soil on a coarse-loamy reclaimed soil of a semi-arid sagebrush steppe. These results may be attributed to conserved soil available moisture beneath the straw as Maurya and Lal (1981) found 2–3% increase in soil moisture under straw mulch cover compared to bare ground controls on sandy loam soils in Nigeria. Ji and Unger (2001) found that straw mulch significantly increased soil water accumulation compared with bare soil in a laboratory setting using clay loam and clay soils.

Straw mulch had a negative to neutral impact on VGS soil, compared with GLS and SL soils. Straw suppressed establishment, species richness, and diversity and had a negligible effect on the aboveground biomass. This is likely due to reduced soil moisture as described by Gill and Jolota (1996) where straw keeps the surface moist and causes larger soil moisture losses to evaporation through hydraulic conductivity. Without straw, a dry layer quickly forms which breaks the connection to deeper layers and losses from evaporation rapidly decline. The addition of straw may have exacerbated the already dry conditions in the excessively well-drained VGS soil. While this straw mulch drying effect has been shown in soils with 76% but not with 59% sand (Jalota et al., 2001), GLS soil averaged 76% and SL averaged 68% sand but both benefited from the addition of straw mulch. The ubiquitous presence of gravel likely reduces hydraulic conductivity in all of our soils and makes it difficult to predict a threshold texture for recommending straw addition other than it is below 88% and above 76% sand in our study.

The addition of fertilizer to the straw increased aboveground biomass for GLS and SL soils but reduced establishment which resulted in fewer, but bigger plants. The fertilizer removed the positive effect of the straw on species richness and diversity, returning both to levels similar to bare ground. The decrease in richness with an increase in biomass is similar to other studies (e.g. Reynolds et al., 2007) but there seems little consensus about the impact of fertilization on seeded sites (e.g. Newman and Redente, 2001; McGeehan, 2009) other than weedy species and grasses often benefit more than natives (Anderson & Ostler, 2002; Baer et al., 2003; Gendron and Wilson, 2007; Sparke et al., 2011; among others). Unlike the GLS and SL soils, biomass, establishment, richness and diversity decreased in VGS soil with the addition of fertilizer. The growth rate of the plants could have increased with fertilization which made them more susceptible to the droughty conditions (e.g. Chapin, 1980) but fertilization is known to make semi-arid plants more susceptible to drought (Snyman, 2002). By staying small without fertilization, the plants were potentially able to survive on the limited available water.

A threshold response to rainfall is expected where low levels do not support vegetation establishment and growth and when some sufficient level is reached vegetation is supported. Another threshold occurs between that level and the level where water is no longer the limiting factor for additional vegetation growth—at that point more water no longer results in improved establishment or growth. Our low rainfall treatment was near the point where water was insufficient for vegetation but the average and high rainfall treatments were both well past the inflection point for sufficient water and the high treatment may have been near the level were water was no longer the limiting factor. When straw mulch was used alone, it augmented aboveground biomass under low and average rainfall scenarios, but not when the rainfall amount was high showing that the conserved moisture did not benefit the plants. Under the high rainfall scenario, adding fertilizer helped the plants to produce greater aboveground biomass. The benefit of fertilizer was not evident under both low and average rainfall scenarios, where water was probably still the limiting factor for additional growth. Researching the vegetation response to increasing rainfall between the low and average rainfall treatments may allow a better assessment of how frequently rainfall amounts are consistent with vegetation benefiting from straw addition.

One drawback to using mulches in arid and semi-arid areas has been that the wind can quickly move the mulch off site (Groen and Woods, 2008) and the target site has wind through much of year. A solution to this problem has been to use a spray-on tackifier to adhere the mulch together and to the soil surface. A common tackifier is an anionic polyacrylamide (PAM), which is also used for erosion control and infiltration management but is not without environmental concerns (Orts et al., 2007; Sojka et al., 2007). In this study, we used PAM as a tackifier to simulate the expected practice required if mulch is used on the target site but PAM may not be without effects, albeit small, other than just holding the straw in place. Several studies have found decreased plant establishment and growth with PAM application and there is the suspicion that PAM has negative effect on soil microbial organisms (Sojka et al., 2006). Another study found that PAM has variable effects on soil microbial population including nematodes, bacteria, fungi, and actinomycetes (Kay-Shoemake et al., 1998). Application of PAM can also have variable effects on soil aggregate formation and residual soil water content depending on application rate and soil texture (Nadler and Steinberger, 1993; Ross et al., 2003; Orts et al., 2007). Because we used the PAM tackifier combined with the mulch treatment, the effects could not be examined on plant establishment and growth. It is difficult to see how surface mulch could be used on extensive revegetation projects in many windy semi-arid grasslands without being combined with other practices such as using a tackifier to keep it place until vegetation establishes.

5. Conclusion

There was some establishment and growth across all levels of the treatments albeit reduced in the low rainfall scenario and on the excessively well-drained VGS soil. Given that rainfall amounts cannot be known ahead of time, this shows that with a diverse species mix, some plants can be established even in bad years on poor sites. However, this might also suggest that seeding efforts need to take place across multiple subsequent years after poor germinating or growing conditions occur or to reach specific target community composition (e.g. Conrad and Tischew, 2011).

While many prescriptions for successful reclamation exist, the specific site conditions ultimately determine which amendment and construction practices will result in the successful establishment of a stable and self-sustaining plant community. The soil texture and structure play an important role in revegetation and should be given as high a priority during construction as landform and grading. The decision to apply straw mulch on semi-arid areas is complicated due to the influences of soil texture, rainfall, and wind but straw mulch remains a useful tool in many situations. The addition of fertilizer was not helpful in most respects but a longer window of observation may be needed. The threat of non-native weed invasion with fertilizer makes it less attractive given the limited benefit and negative effects in some situations. Small scale field testing is recommended ahead of large scale revegetation efforts in order to establish the relative merits of proposed revegetation practices.

A larger field-scale research effort is under way to determine how closely these greenhouse results correspond to field results on soils these samples come from and with the tackified straw and bare soil treatments. While there is every expectation and indication that the greenhouse and field trials will give similar results, the consistency of greenhouse-field comparability remains the primary weakness of this kind of study. However, small greenhouse and plot research has much to offer for reclamation projects because samples of soils are often available well before the disturbance takes place or before revegetation occurs. This can allow much testing or trial-and-error evaluation of potential revegetation practices, potential species, and assessment of the chance of success in different rainfall scenarios. This information is more timely ahead of the reclamation start and can be difficult/expensive to arrange at larger scales.

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