RAINSPLASH-INDUCED MOUND DEVELOPMENT BENEATH DESERT

SHRUBS:

MODULATIONS OF SEDIMENT TRANSPORT AND STORAGE,

WITH IMPLICATIONS FOR HILLSLOPE EVOLUTION

By

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To Josh

My other half and my partner in balding

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CHAPTER I

INTRODUCTION

Rainsplash transport, or the motion of soil grains initiated by raindrop impacts, as a mound forming process is a well documented phenomenon (Carson and Kirkby, 1972; Parsons et al., 1992; Wainwright et al. 1995; Bochet et al., 2000; Wainwright et al., 2000; Childs, 2008; Furbish et al., 2009). Previous emphasis has been placed on the physics of rainsplash transport (Furbish et al., 2007), as well as on mound characteristics (Parsons et al., 1992; Wainwright et al., 1995; Childs, 2008).

At its most fundamental level, rainsplash transport occurs as momentum is transferred from a falling raindrop to loose soil grains (Furbish et al., 2007). By this momentum transfer, a raindrop can cause sediment transport in two ways. For very fine sand, particles become entrained in the splash corona and are transported as "blobs" of sand and water (Taube et al., 2009). For coarser sand, grains are too large to be held within water drops. Instead, momentum from a raindrop is transferred by grain-to-grain collisions and grains are ejected radially about the impact site ahead of the splash corona (Furbish et al., 2007).

On level surfaces, grain motions initiated by rainsplash are radially symmetrical about the center of impact. However, on an inclined surface, grain trajectories take on a more asymmetrical distribution whereby net soil transport is downslope (Furbish 2007) (Figure 1). The distance that grains are splashed is controlled by both grain size and

hillslope gradient, among other factors such as drop size and drop velocity.

Legout et al. (2005) and Leguedois et al. (2005) demonstrate that maximum average splash distances are achieved for grain-size fractions with mean grain diameters between 0.1 and 0.2 mm. Grains of this size travel approximately 20 cm upon impact from drops with a mean diameter of 1.7 mm. Average splash distances for grains larger than 0.2 mm decrease rapidly, with the smallest splash distances of 5-10 cm for grains with diameters around 1 mm. Grains smaller than 50 μm have splash distances between 8 and 15 mm. A decrease in splash distance for very fine sediment is consistent with the idea that very fine sediment travels as clumps of grains held within splashed water droplets, which act as larger grains.

Taube et al. (2009) demonstrates another phenomenon that occurs with varying grain sizes in relation to rainsplash. Finer grained sand has a higher ejection angle that is more comparable to the angle of the splash corona than coarser material (Figure 2). As a result, finer grained sediment travels farther than coarser sediment. This trend continues for progressively finer sediment until grains begin to clump together as described above. In
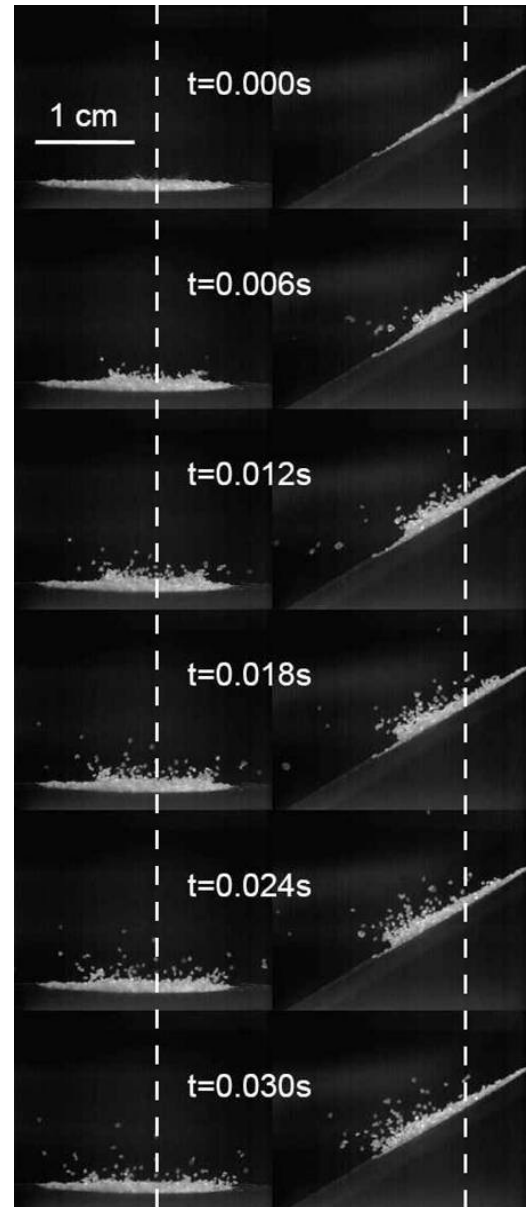

Figure 1. High speed image of a raindrop impact on medium sand. Note the asymmetry of sediment trajectories on a slope, as compared to the radial symmetry of grain trajectories on a horizontal surface; from Furbish et al. (2009).

addition to the effect of decreasing grain size, grain splash distance increases with increasing hillslope gradient (Moeyersons and Deploey, 1976; Furbish et al., 2007).

In the absence of vegetation and assuming uniform rainfall across a hillslope with uniform gradient, rainsplash transport moves sediment downslope. But assuming an

Figure 2. High speed image of a raindrop impact on fine versus coarse sand. Grain trajectories of very fine sand have higher ejection angles than medium sand. Also note the clumps of wetted grains ejected from the top image, whereas single grains are ejected in coarser sediment; from Taube et al., (2009).

inexhaustible supply of detachable sediment there is no change in hillslope topography. The same amount of sediment transported downslope by rainsplash is replaced by sediment splashed from farther upslope. In other words, sediment transport on the hillslope is at steady-state. However, in the presence of a shrub population, variations in rainsplash sediment storage develop, leading to fluctuations in sediment transport.

The canopy cover provided by a shrub protects soil beneath the shrub from raindrop impacts. During rain events, grains are splashed beneath shrubs where they are shielded from falling drops by the shrub canopy. Because fewer raindrops strike the soil beneath a shrub, fewer grains are ejected away from the shrub. This preferential movement of

sediment beneath shrubs leads to sediment-mound formation because more sediment is deposited beneath the shrub than is removed by rainsplash (Parsons et al., 1992). In many studies, mounds exhibit finer grain sizes than areas outside of the mounds, presumably because finer grains are splashed farther and tend to accumulate underneath shrubs faster than coarser material (Parsons et al., 1992; Wainwright et al., 1995; Caldwell, 2008).

Whereas much of precipitation is intercepted by shrub canopies, some rain does reach the ground surface as either clear throughfall or intercepted throughfall (Brandt, 1989). Clear throughfall reaches the ground surface without touching canopy cover. Therefore, raindrops that reach the ground as clear throughfall splash sediment as though the soil was exposed to direct rainfall. In contrast, intercepted throughfall is the drops that reach the ground after collecting on a leaf or stem surface and dripping down to the ground surface. These raindrops will splash some sediment away from a mound, and eventually a steady-state condition will be reached whereby the same amount of sediment is splashed under a shrub as is splashed away from a shrub.

Sediment continues to accumulate in mounds beneath shrubs until the shrubs die and the underlying soil is exposed to rainsplash erosion. On a hillslope scale, sediment is stored in mounds as long as an entire community of shrubs is thriving. During the lives of these shrubs, they act as sediment "capacitors", storing sediment and preventing sediment from being transported downslope. For two common desert shrubs observed at our field sites, broom snakeweed and rabbitbrush, sediment is stored in mounds on decadal time scales. For example, Ralphs and Sanders (2002) studied a broom snakeweed population that went through two population cycles in a 13-year span. Rabbitbrush is typically a longer lived shrub, with some populations living to 50 years or more (Toft and Fraizer, 2003).

Other desert shrubs, such as creosote and sagebrush, can also serve as sediment capacitors, surviving for several decades (Perryman et al., 2001; Whitford et al., 2001).

Whereas many studies have focused on how mounds develop by rainsplash, none has investigated what effect mound development has on hillslope sediment flux. As described above, rainsplash sediment transport increases with increasing hillslope gradient, and conversely, decreases with lower hillslope gradients. Modeling presented in this study shows that as sediment is stored in mounds, landscape elevation decreases downslope of a mound because sediment that is transported by rainsplash is not replaced by upslope sediment that is held in mound storage. This leads to a decrease in hillslope gradient immediately downslope of a shrub, and thus a local decrease in sediment flux occurs.

When a shrub dies, the underlying mound is exposed to rainsplash transport, and because the sides of a mound have higher gradients than the overall hillslope, local sediment flux increases. These modulations in sediment flux due to the interactions between desert shrubs and soil transport potentially can have important implications for sediment transport and hillslope evolution.

The purpose of this study is to describe the effect that mound development by rainsplash erosion has on hillslope sediment transport in semi-arid environments. Topographic and vegetation surveys are described for two field sites in the Cibola National Forest, New Mexico. These field measurements are used to inform a mass-conserving sediment transport model that gives insight into how shrub populations on desert hillslopes and subsequent mound growth act to modulate downslope sediment flux. Implications for hillslope evolution on geomorphic timescales are discussed.

CHAPTER II

METHODS

Field methods: Shrub and topographic surveys

Topographic Surveys

Topographic surveys were conducted in May 2009 on three hillslope plots in the Cibola National Forest, New Mexico (Figure 3). At Arrowhead Well 1, a 20m x 20m area was marked off with a tape

Figure 3. Location map of topographic and vegetation survey sites.

measure. Elevation measurements were taken using stadia rod and transit at two meter intervals in a grid pattern. At Arrowhead Well 2, the surveyed hillslope was smaller, so a 10m x 16m plot was used, also with elevation measurements taken at two meter intervals. At Placitas, elevation was surveyed over a 20m x 20m plot at one meter intervals.

Vegetation Surveys

At Arrowhead Well 1 and Placitas 1, complete vegetation surveys were conducted. Every shrub within the survey plot was mapped in relation to the topographic survey grid. Each shrub was identified as specifically as possible, and measurements were taken of shrub height and canopy breadth. Maximum stem diameter was measured for rabbitbrush at Arrowhead Well 1 and was determined by looking near the base of a shrub for the largest exposed stem diameter. In cases where the underlying shrub mound covered some stems at the base, only stems exposed at the surface were considered to represent the largest stem diameter. A few of the rabbitbrush at Arrowhead Well 1 had relatively large, woody bases exposed at the land surface. These also were not considered stems because it appeared that stems branched out from this base.

Additionally, shrubs were selected from each site that seemed to represent different stages of shrub maturity (determined by size) to measure the height and breadth of underlying mounds. Whereas mound topography was at times subtle, efforts were made to identify the perimeter of a mound at an inflection point where the sides of a mound reached zero slope. Mound height was measured from the surrounding ground surface to the point where mound and shrub base met.

Soil Sampling

Soil samples were collected from beneath shrubs (mound regions) as well as from areas outside of canopy cover (intermound regions) to analyze for grain size and soil organic content (SOC). Grain size was analyzed on a Malvern Mastersizer 2000. To

remove any plant litter from the soil, all samples were screen sieved and material larger

than 2 mm was removed. SOC is measured by a loss on ignition (LOI) protocol.

Approximately 10 g of sample are measured and put into small porcelain crucibles.

Samples in the crucibles are then weighed and placed in a 100 ºC oven to dry (at least 12

hrs). Samples are stored in the oven until they are placed in the furnace. After the

samples are removed from the drying oven, they are weighed again and kept in a

desiccator until they are placed in a muffle furnace. Samples are cooked in a muffle

furnace at 450 ºC for 8 hours, and are removed and placed in a desiccator until the

crucibles cool enough for handling. The samples are weighed one final time, and the

difference in mass from after drying to the mass after combustion in the furnace is

assumed to be the amount of SOC.

Modeling methods

Equations

The modeling work presented in this study is based on the Fokker-Planck

equation, which is used to describe diffusion of the land surface, and an exponential

equation that describes shrub canopy growth.

Adriaan Fokker and Max Planck first used the Fokker-Planck equation to

describe Brownian motion, or random walks, of particles (Risken, 1996). Following

work by Elise Childs (2008), the Fokker-Planck equation takes the following form:

$$\frac{\partial \zeta}{\partial t} = -\frac{\partial}{\partial x}(\gamma u) - \frac{\partial}{\partial y}(\gamma v) + \frac{1}{2}\frac{\partial^2}{\partial x^2}(\gamma D) + \frac{1}{2}\frac{\partial^2}{\partial y^2}(\gamma D), \qquad (1)$$

where ζ [L] is land-surface elevation, γ [L] is grain activity, or the volume of sediment in motion per unit area, u [Lt^{-1}] is the mean velocity of downslope grain movement, and D [L^{2}t^{-1}] is the diffusion coefficient. Assuming that velocity of grain motion is proportional to surface slope,

$$u = -K\frac{\partial \zeta}{\partial x} \quad \text{and} \quad v = -K\frac{\partial \zeta}{\partial y}, \tag{2}$$

where K is a transport coefficient. Substituting and bringing constants outside of the derivatives gives,

$$\frac{\partial \zeta}{\partial t} = K\frac{\partial}{\partial x}(\gamma\frac{\partial \zeta}{\partial x}) + K\frac{\partial}{\partial y}(\gamma\frac{\partial \zeta}{\partial y}) + \frac{D}{2}\frac{\partial^2 \gamma}{\partial x^2} + \frac{D}{2}\frac{\partial^2 \gamma}{\partial y^2}. \tag{3}$$

In the first two terms on the right side of the equation, soil particles are advected down a hillslope in proportion to surface gradient. It is important to point out a few key characteristics of this description of landscape evolution. First, soil particle advection, and in turn land surface elevation diffusion, are driven by gradients in both grain activity and topography. On a flat hillslope in the absence of a shrub community, there is no topographic or activity gradient, and $\partial \zeta/\partial t$ equals zero.

However, as a shrub grows, grain activity beneath the canopy decreases, leading to a divergence of flux, and thus a mound develops. With mound development, $\partial \zeta/\partial x$ is no longer constant for some areas of the hillslope, namely, those covered by shrub canopies, and $\partial \zeta/\partial t$ is a changing quantity. Thus, the landscape evolves.

Turning to the third and fourth terms on the right side of the equation, we see that

(D/2)$\partial^2\zeta/\partial x^2$ and (D/2)$\partial^2\zeta/\partial y^2$ take the form of diffusion expressions. Note, however, that

rather than the second derivative of elevation with respect to space, this term involves the

second derivative of grain activity with respect to space. In this sense, this term results in

mass diffusion as grains move from areas with high grain activity (exposed soil) to areas

with low grain activity (beneath shrubs).

These two terms continue to change as a growing shrub alters grain activity

beneath its canopy. However, after a shrub dies, we assume that the canopy is

immediately removed. Therefore, local grain activity where a shrub used to be is the

same as the background grain activity for bare soil, and the activity ratio equals one. In

actuality, the "skeleton" of a dead shrub will remain for some period of time after death,

providing some degree of protection from rainsplash.

For illustration, assume that after the death of a shrub, grain activity on the entire

hillslope is equal to one. Thus,

$$\frac{\partial \zeta}{\partial t} = \kappa \frac{\partial^2 \zeta}{\partial x^2} + \kappa \frac{\partial^2 \zeta}{\partial y^2} , \tag{4}$$

where κ is the product of K and γ, or the hillslope diffusivity. This equation takes the

standard form of a diffusion equation. Therefore, after a shrub dies and there is no longer

an activity gradient, diffusion smooths the land surface and removes the mound.

Turning to shrub growth, we assume that shrub canopy growth goes as

$$R(t) = R_0 + (R_f - R_0)(1 - e^{-t/T}) , \tag{5}$$

where $R(t)$ is shrub radius, R_0 is initial shrub radius, R_f is final shrub radius, t is shrub age,

and T is a characteristic time constant (Furbish et al., 2009). Whereas Furbish et al. (2009) determined T such that a shrub canopy reaches 90% maturity within an assumed period of time, here T is calculated from shrub measurements collected in the field. For our field site, which mostly involves rabbitbrush, we assume that the maximum stem diameter on a rabbitbrush shrub is proportional to the age of the shrub. Therefore, a shrub on a hillslope with the largest maximum stem diameter is assumed to be the oldest shrub. For our site, the maximum stem diameter for rabbitbrush was 4.5 mm. We recorded stem diameters of 7 and 8.4 mm, but those measurements seemed to be of exposed roots rather than stems, therefore they are not considered to be the oldest shrubs. We also assume that the largest stem diameters (~4 mm) represent a fully mature shrub, and assign a maximum age to the shrub with the largest shrub diameter.

According to Toft (2003), 50 years is a reasonable adult age for rabbitbrush. In the present study, a time constant, T, is calculated assuming maximum shrub age of 40 years. Rearranging (5), we see that

$$\ln(1 - \frac{R(t) - R_0}{R_f - R_0}) = -\frac{1}{T} t .$$ (6)

Equation 6 has the form of a linear equation, so by plotting shrub age versus the natural log of a shrub canopy radius ratio, the slope of a best fit line will be equal to the negative reciprocal of T. One problem with this approach is the uncertainty in estimating the age of a rabbitbrush shrub. To account for this uncertainty, four different values of T are calculated, assuming adult shrub ages of 20, 30, 40, and 50 years, and the resulting shrub mounds are compared. After determining values for T, we estimate the time it takes for a

shrub to reach 90% of its total mature canopy (Figure 4 and Table 1).

Based on a shrub survey at our field site, we estimate that the average canopy radius for a shrub that was classified in the field as large was 37 cm. From the measured time constant, the time it takes for a shrub canopy to grow to 90% maturity can be calculated. Therefore, for a fully mature shrub with a final canopy radius of 37 cm, times for a shrub with a given final age and time constant to grow to a radius of 33.3 cm are calculated.

Model Development

Equations (3) and (5) are solved by finite differencing in MATLAB. With each time step, a shrub grows according to the shrub growth equation such that as the mathematical shrub canopy grows, more of the area beneath the shrub is protected from rainsplash transport. In the model, this leads to a grain activity gradient expressed as essentially a probability of transport at each node. Grain activity is lowest in the center of a shrub where the canopy above is most dense, and progressively increases away from the center of a shrub to reach a maximum grain activity for bare soil. This activity gradient mathematically causes more sediment to move beneath the shrub than away from the shrub. Thus, a mound forms.

Using digital imagery, Childs (2008) found that the change in canopy cover from the center to perimeter of broom snakeweed shrubs can be described using a parabolic expression. Furthermore, she estimated the maximum coverage in the center of a shrub to be 80%. In this study, modeled shrubs are assumed to be rabbitbrush. From field

observations canopy density appears greater for rabbitbrush than for broom snakeweed. Therefore, maximum canopy cover is estimated to be 90% closed, and the decrease in canopy cover towards the perimeter is described as a fourth-order parabola.

From the slopes of the best fit lines in Figure 4, values of T were determined for shrubs with maximum ages of 20, 30, 40, and 50 years to be 5, 7.1, 9.1, and 11.8, respectively. After determining the appropriate time constants, shrub mounds were simulated and compared for each fully mature shrub to evaluate how sensitive the model
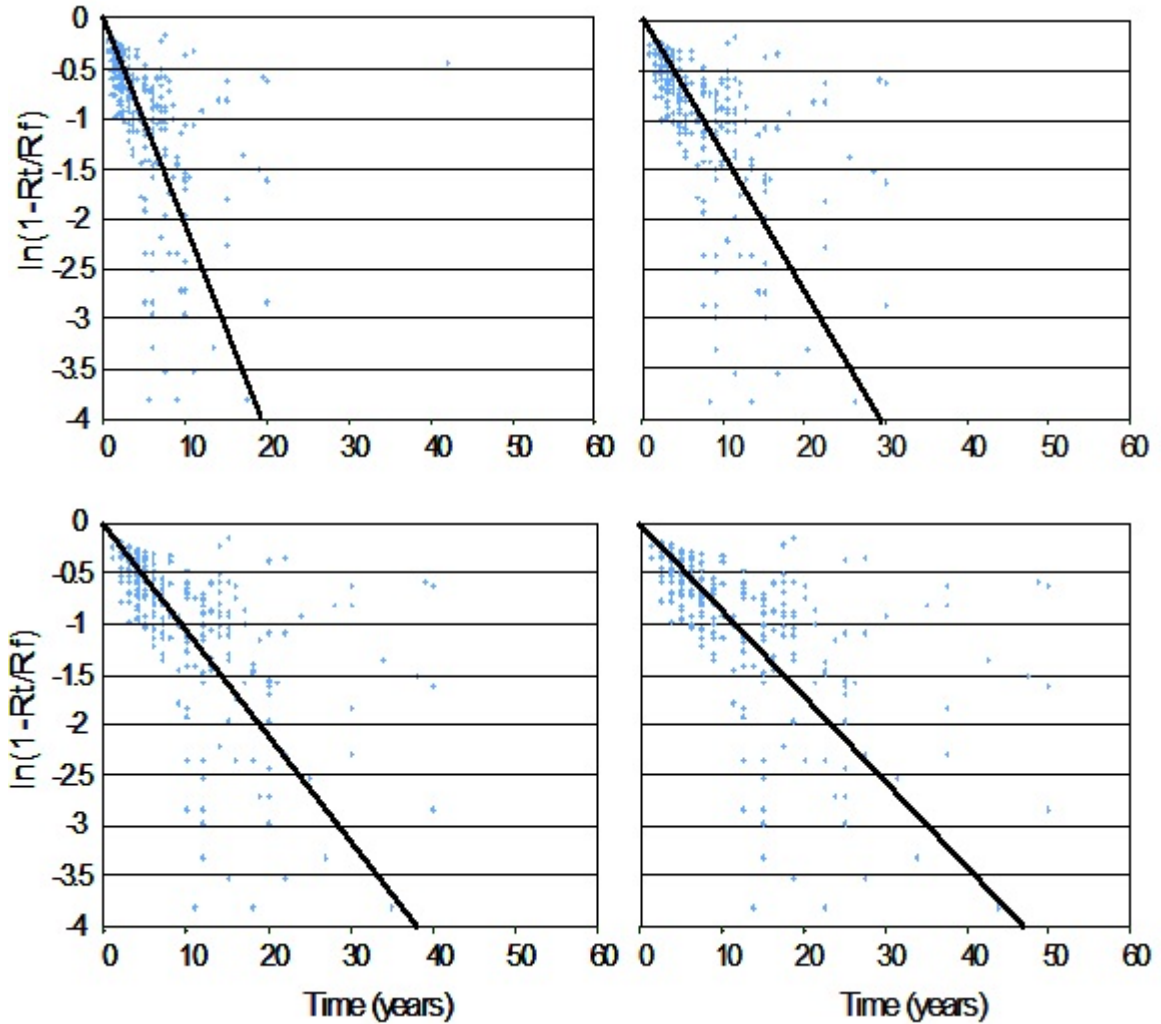
Figure 4. Plots of canopy size versus age for rabbitbrush shrubs at Arrowhead Well 1. Ages are assumed using measured stem diameters, where the largest stem diameter is taken to be either 20, 30, 40, or 50 years, linearly interpolating ages between zero and the maximum age. Best fit lines are forced through (0, 0).

is to different time constants and ages (Table 1).

Table 1.

Shrub age	Age at 90% maturity	Time constant, T	Final mound width (cm)	Final mound height (cm)	Final mound volume, conical (cm^3)	Mound volume at 90% maturity (cm^3)
20	12	5	80	6.3	10600	9720
30	16	7.1	80	7.1	11900	10700
40	20	9.1	80	7.6	12700	11200
50	27	11.8	80	7.9	13200	12000

For the purpose of this study, differences in final mound volumes are assumed to be negligible, especially for the older shrubs (30, 40, and 50 years). Furthermore, it is assumed that these final shrub ages won't significantly affect the interpretation and implications of the model. The average final mound volume of the 30, 40, and 50 year old shrubs (12,600 cm^3) is smaller than the average volume of mounds assumed to be the oldest in the field (16,000 cm^3). Therefore, results of this modeling should not be viewed as an precise simulation of conditions on the surveyed hillslopes, but rather as scenarios that illustrate trends in sediment flux associated with mound growth.

CHAPTER III

RESULTS

Field Results

Topography:

Contour maps of Arrowhead Well 2 and Placitas 1 show hillslopes with fairly uniform gradients of approximately 3.8º and 4.8º, respectively (Figure 5). Arrowhead Well 1shows the most spatial variability in topography, with two slight depressions in the western (lower right) corner of the plot. However, Arrowhead Well 1 also has the lowest gradient with a slope of approximately 0.6º. Therefore, the topographic variation here is very subtle. To the naked eye, Arrowhead Well 1 appears essentially flat.
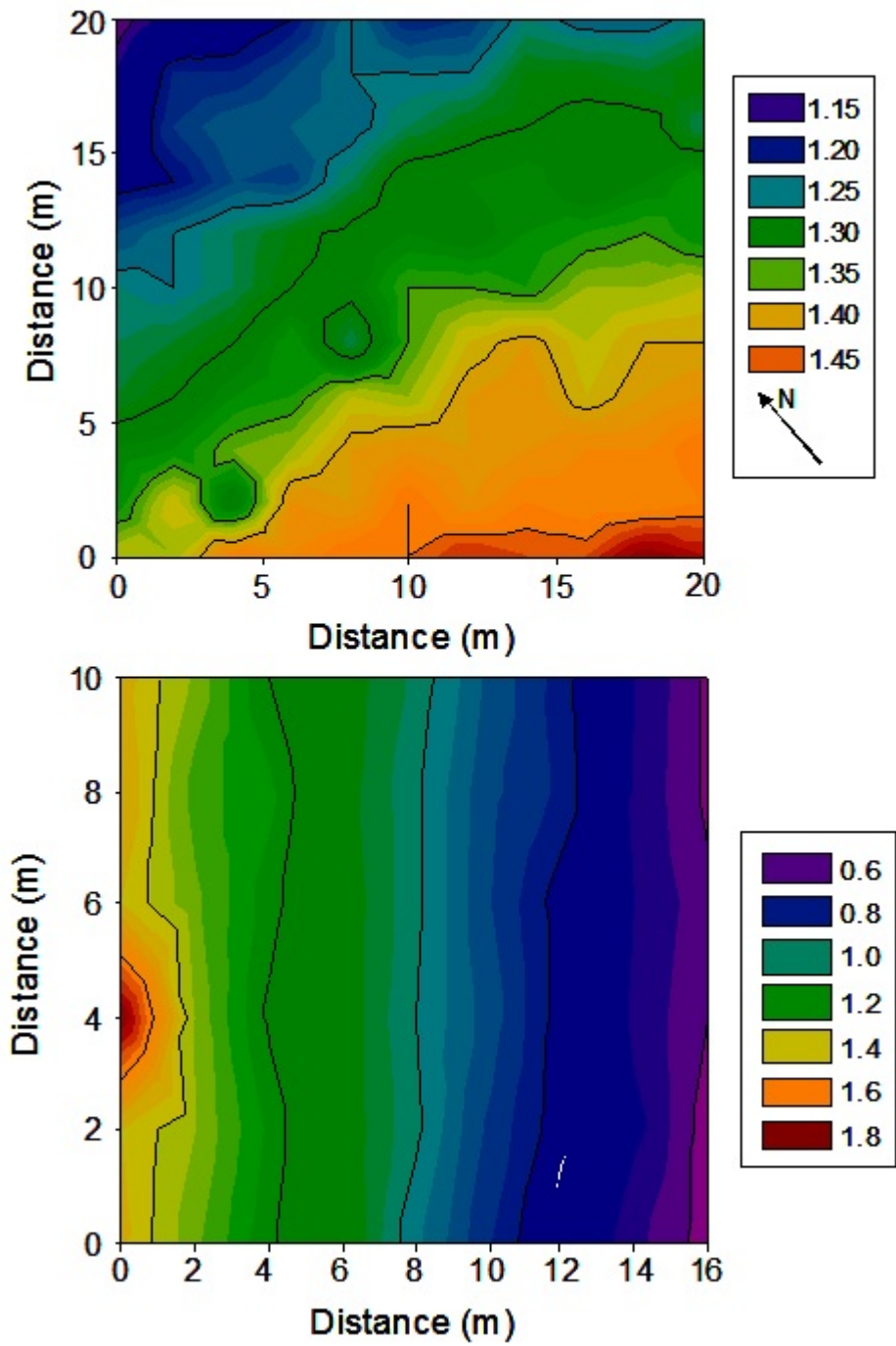
Figure 5. Topographic maps of survey plots at Arrowhead Well 1 (top) and 2 (bottom) and Placitas 1 (next page). Average gradients at Arrowhead Well 1, Arrowhead Well 2, and Placitas 1 are 0.6°, 3.8°, and 4.8°, respectively.
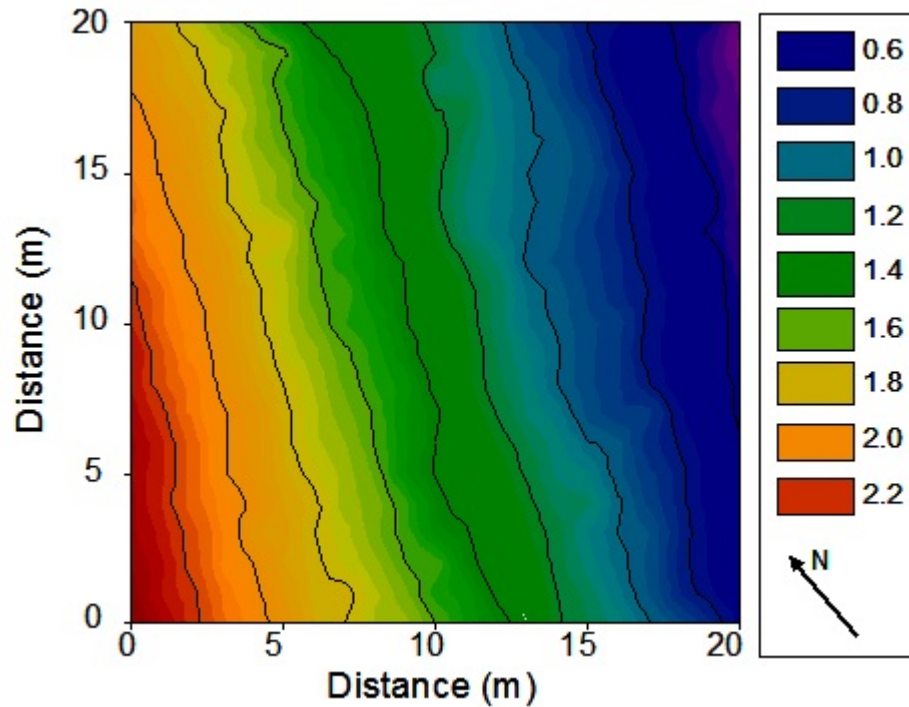
Figure 5. (continued) Topographic map of survey plot at Placitas 1.

Vegetation

At Arrowhead Well 1 and Placitas 1, there were 270 and 364 shrubs, respectively, in each 20m x 20m plot (Figure 6). This gives shrub densities on the hillslopes of roughly 0.68 and 0.91 shrubs per square meter, although shrubs are not uniformly distributed on the hillslope. The shrubs at Arrowhead Well 1 are almost exclusively rabbitbrush, whereas there is more variability in plant species at Placitas 1. Among the 364 plants measured at Placitas 1, there were eight cacti, three yucca plants, and one tree sapling, possibly cedar. Cacti, yucca, and the cedar sapling have been omitted for the purpose of illustrating only shrub cover on the hillslope. It is unlikely that significant mounds would form beneath either cacti or yucca. The cacti observed in the field were

low and laterally extensive, so whereas they would offer almost complete cover of the

underlying soil, there is not enough space beneath them to allow for mound development.
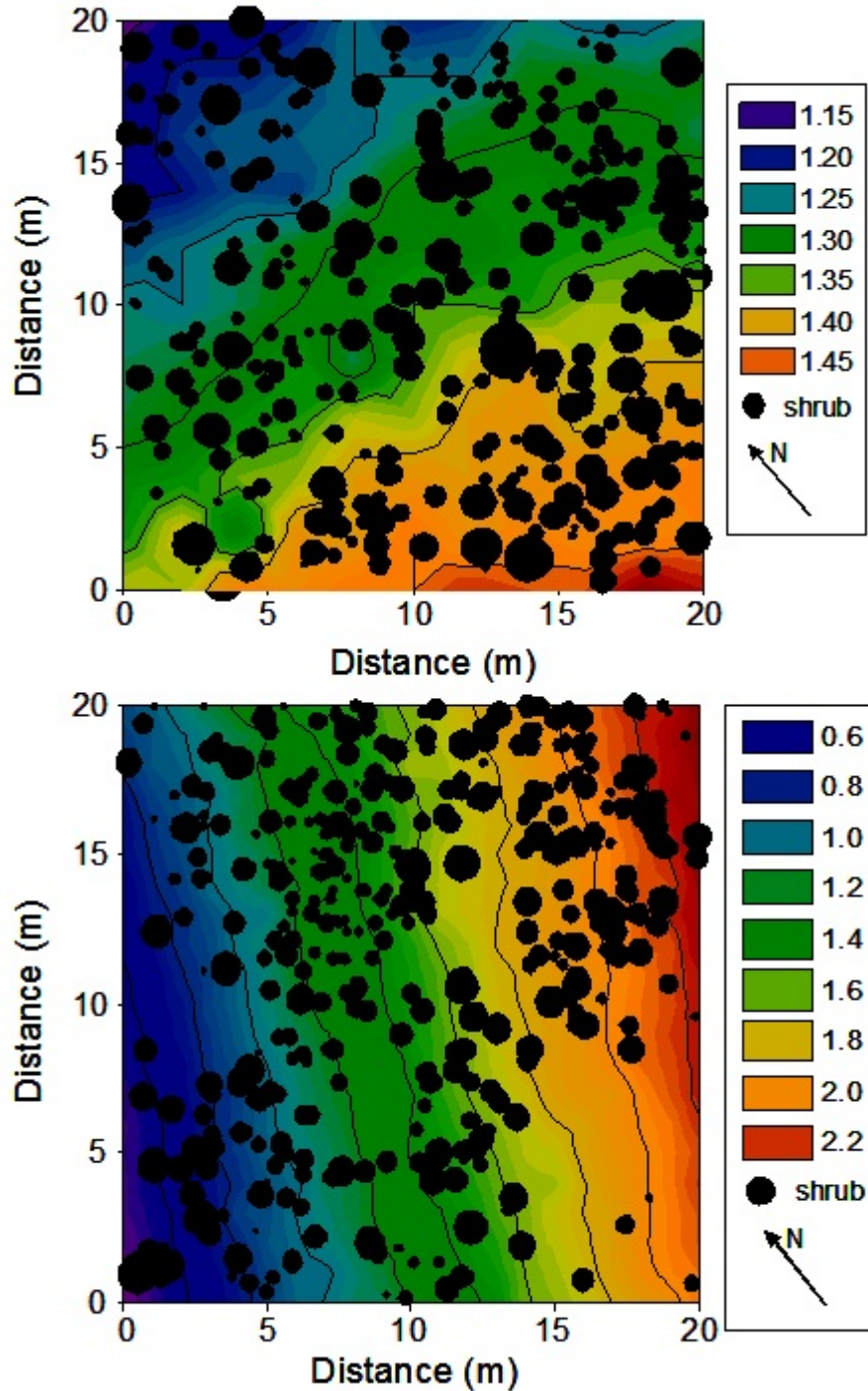
Figure 6. Shrub surveys at Arrowhead Well 1 and Placitas 1. Note that shrub dots are sized proportionally to one another but are not to scale on the hillslope. Whereas some dots overlap on this figure, shrub canopies do not overlap at these two sites.

Although the distribution of shrubs at Placitas 1 is not uniform, the large bare area in the southern (lower left) corner of the survey is partially explained by the omission of two large cacti centered at (17.7, 6.1) and (17.5, 2.6). Those two cacti combined have an area of about 2.4 square meters. Note that throughout this section, the format of coordinates reported for field and modeled results are (x-position, y-position), and all units are in meters.

The largest exposed stem diameters on rabbitbrush are assumed to be proportional to shrub age, with the assumption that shrubs with larger stems (~ 4 mm) have been growing longer, and are therefore older, than shrubs with smaller stems (~1 mm). Stem
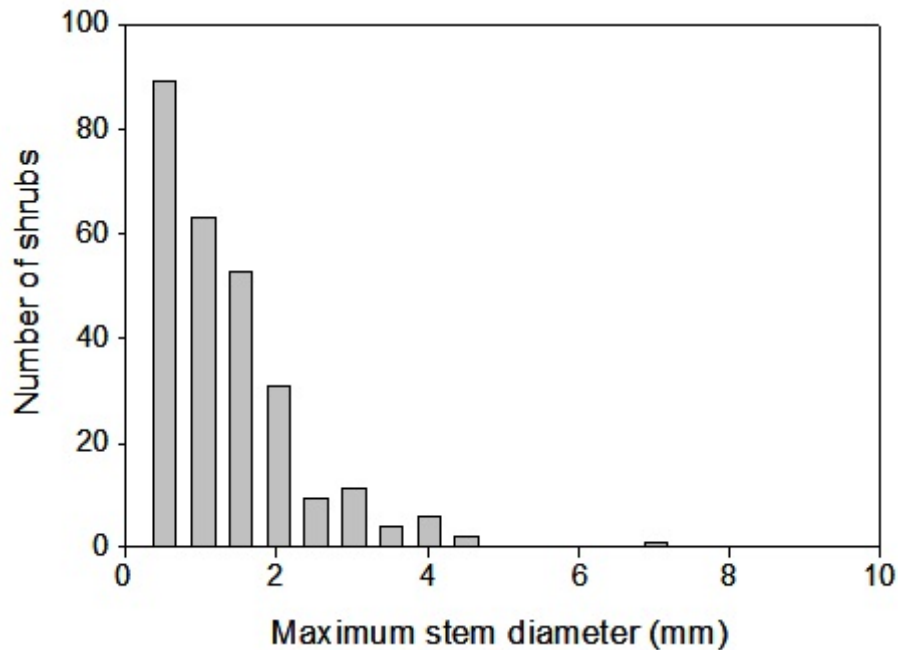
Figure 7. Stem diameter distribution at Arrowhead Well 1.

distributions at Arrowhead Well 1 suggest that the rabbitbrush population is predominantly young shrubs, with the number of adult shrubs tapering off (Figure 7).

Although stem diameters were not measured for broom snakeweed at Placitas 1,

canopy breadth shows a fairly normal distribution spread about a peak breadth of 40 cm.

By contrast, canopy breadth of the Arrowhead Well 1 rabbitbrush are also centered about

a peak breadth of ~35-40 cm, albeit with a wider spread (Figure 8). Whereas assumptions
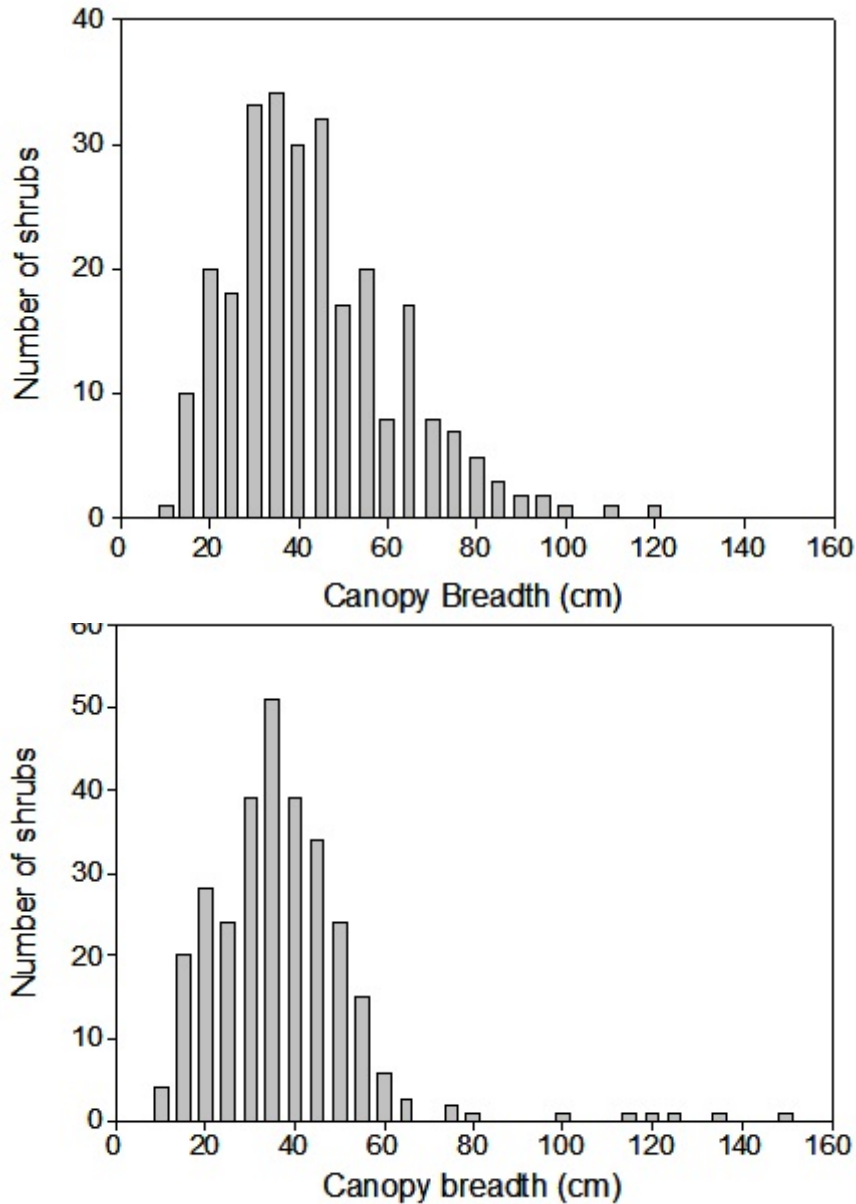
Figure 8. Canopy breadth distribution at Arrowhead Well 1 (top) and Placitas 1 (bottom). Canopy breadth is measured as the average of two perpendicular measurements of canopy diameter.

about shrub age will be made in subsequent sections based on stem diameters of rabbitbrush, no attempts are made at estimating shrub age from measured canopy breadths.

Mound and canopy areas have a fairly close correlation, with canopy area being roughly equal to the area of the underlying mound. For broom snakeweed at Placitas 1, mound area tends to be slightly larger than the associated canopy. In contrast, mounds beneath rabbitbrush at Arrowhead Well 1 and Arrowhead Well 2 tend to be slightly smaller than the overlying canopy.

The shrubs selected for mound measurements fall into three categories: small, medium, and large, with average canopy breadths of 78, 49, and 31 cm, respectively. Associated mound volumes are smallest for the smallest shrubs, and average mound volumes increase as the overlying canopy size increases. Average mound volumes associated with small, medium, and large shrubs are approximately 1,000, 5,000, and 16,000 cm^3, respectively.

Soil

Soil samples from Arrowhead Well 1 and Placitas 1 generally indicate higher SOC values from mound samples than are observed in intermound samples. At these two sites, average mound SOC is 3.3%, whereas average intermound SOC is 1.7%. Mound and intermound samples from Arrowhead Well 2 show no significant differences in SOC, with average SOC values of 1.7% and 1.8%, respectively (Figure 9).
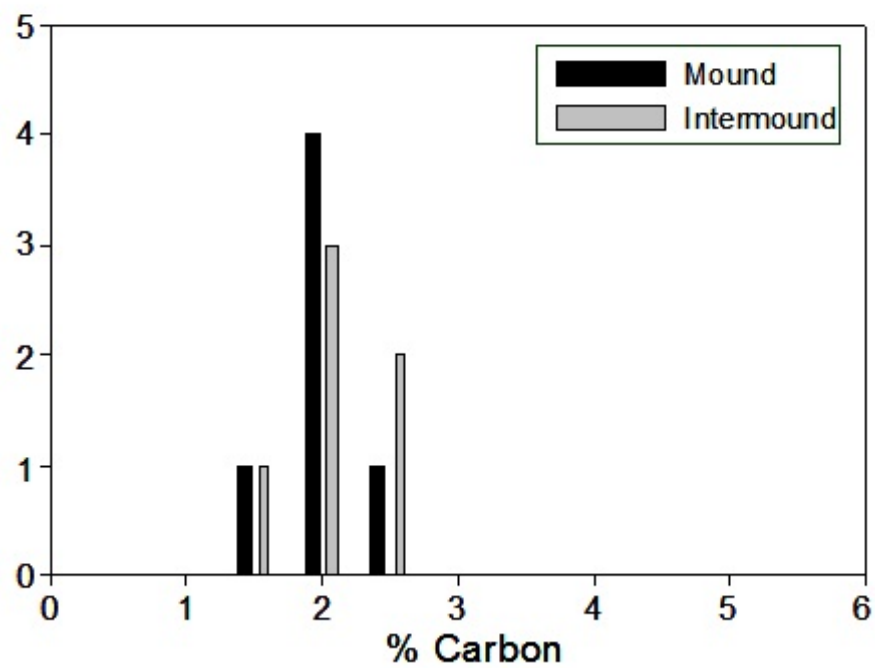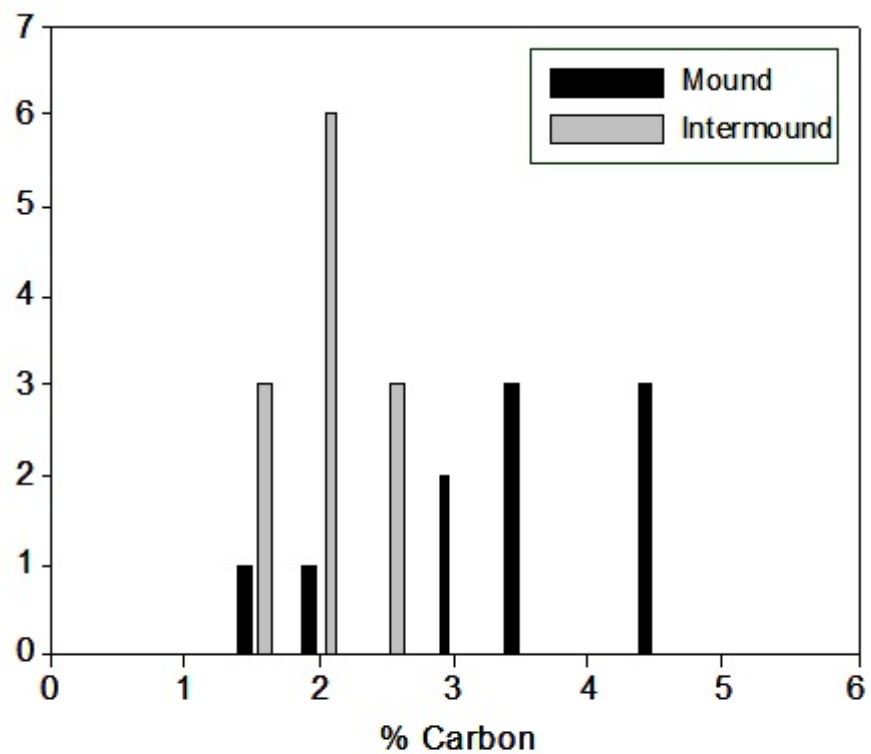
**Figure 9**. Histograms of soil organic carbon (SOC) in samples at Arrowhead Well 1 (top) and 2 (bottom) and Placitas 1 (next page). At Arrowhead Well 1 and Placitas 1, average mound soil samples have higher organic content, presumably from plant litter. Note the low SOC values at Arrowhead Well 2 for both mound and intermound samples.
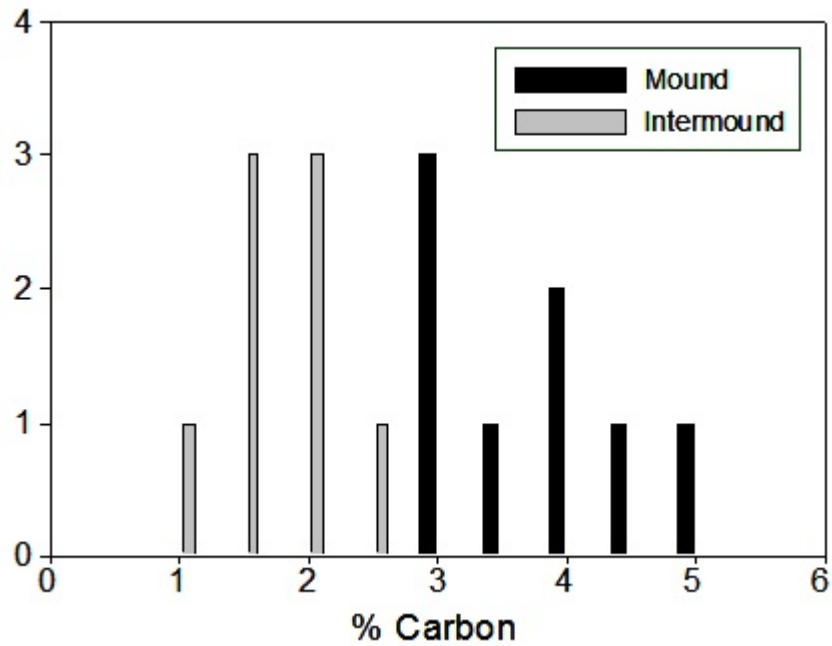
Figure 9. (continued) SOC histograms from soil samples at Placitas 1.

At all three sites, intermound soil samples displayed finer grain sizes than mounds (Figure 10). As with organic content, Arrowhead Well 2 shows the least variability, both within mound and intermound samples, as well as between average mound and intermound grain size distributions. However, intermound samples at Arrowhead Well 2 are slightly finer than mound soil samples. At Arrowhead Well 1 and Placitas 1, mound samples are consistently coarser than intermound samples. Arrowhead Well 1 represents only a subset of soil samples from that site, with eight of the twenty-four total samples represented. Despite this, and based on the consistency in results at the other two sites, it is likely that the characteristically finer grain sizes present in intermound samples is consistent.
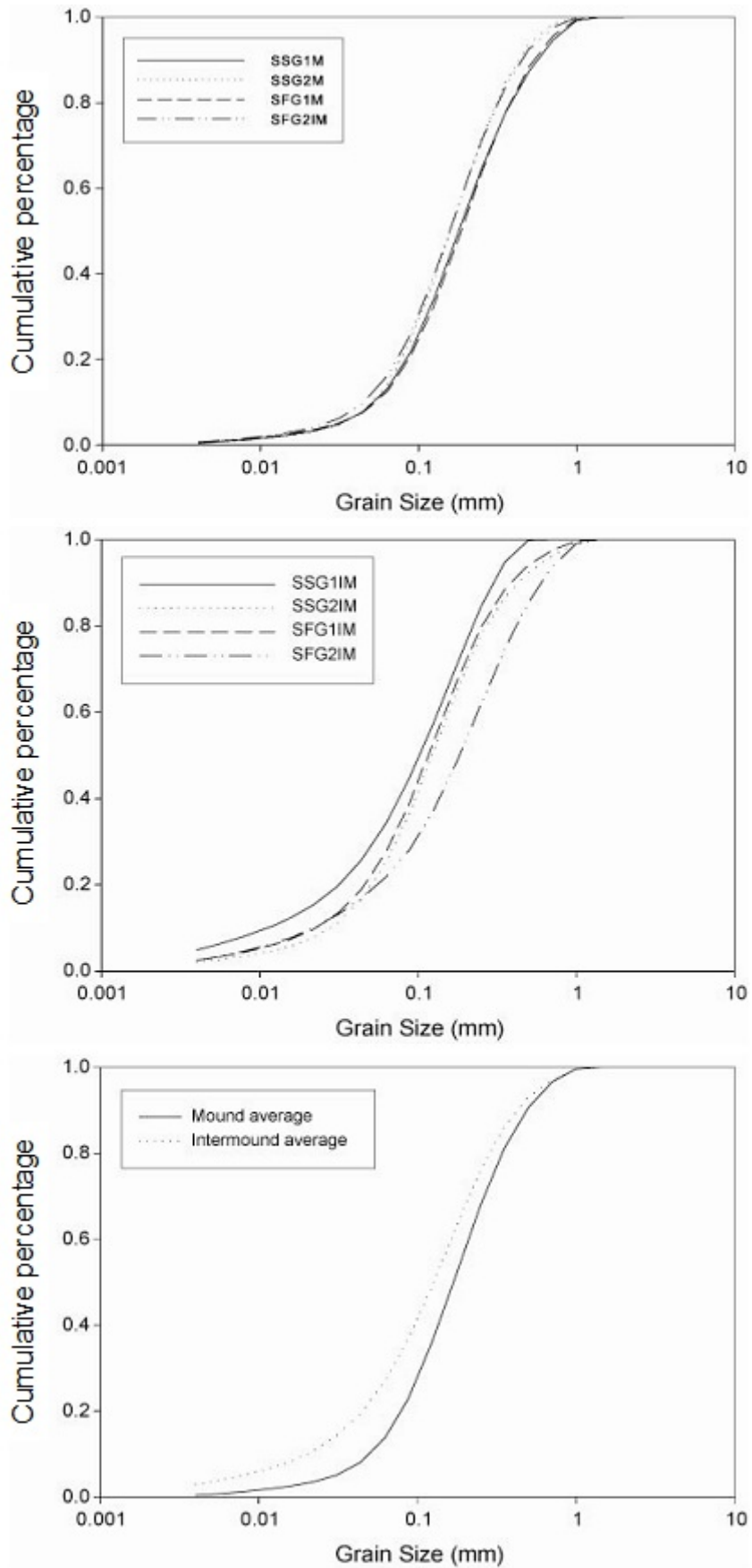
Figure 10. Cumulative grain size distribution plots for Arrowhead Well 1 (this page), Arrowhead Well 2 (next page), and Placitas 1 (p.#). Note that on average, mounds are composed of finer grains that intermound areas.

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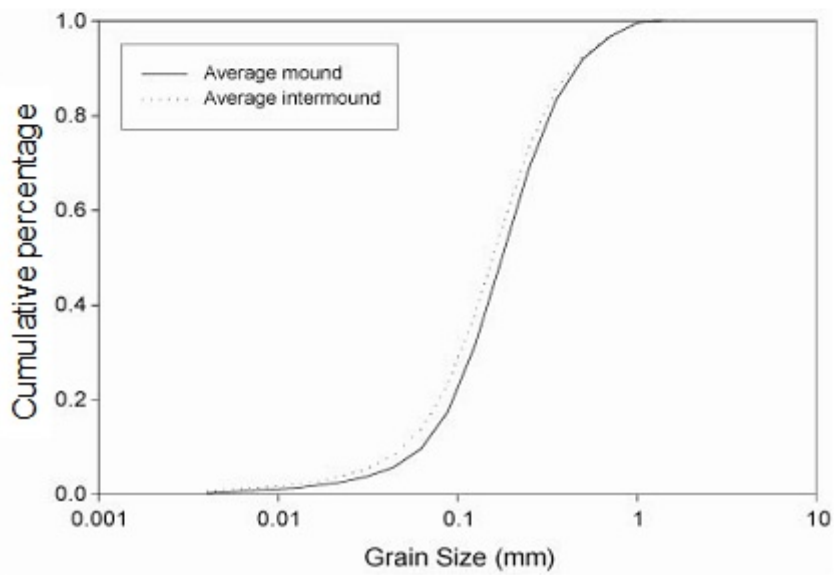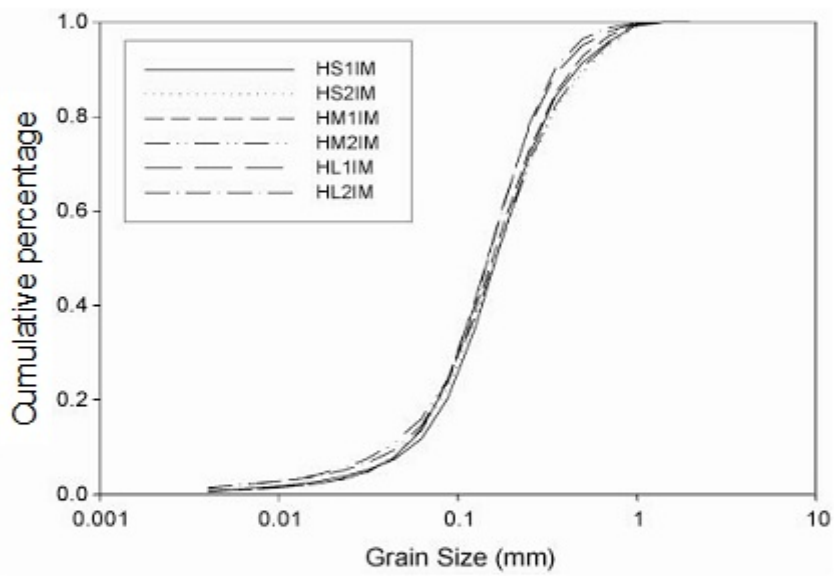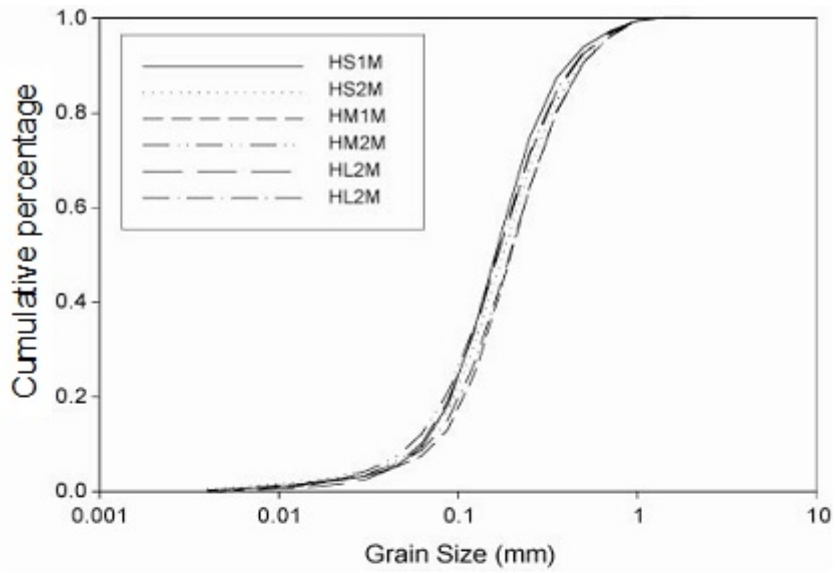
Figure 10. (continued) Cumulative grain size distribution plot for Arrowhead Well 2.
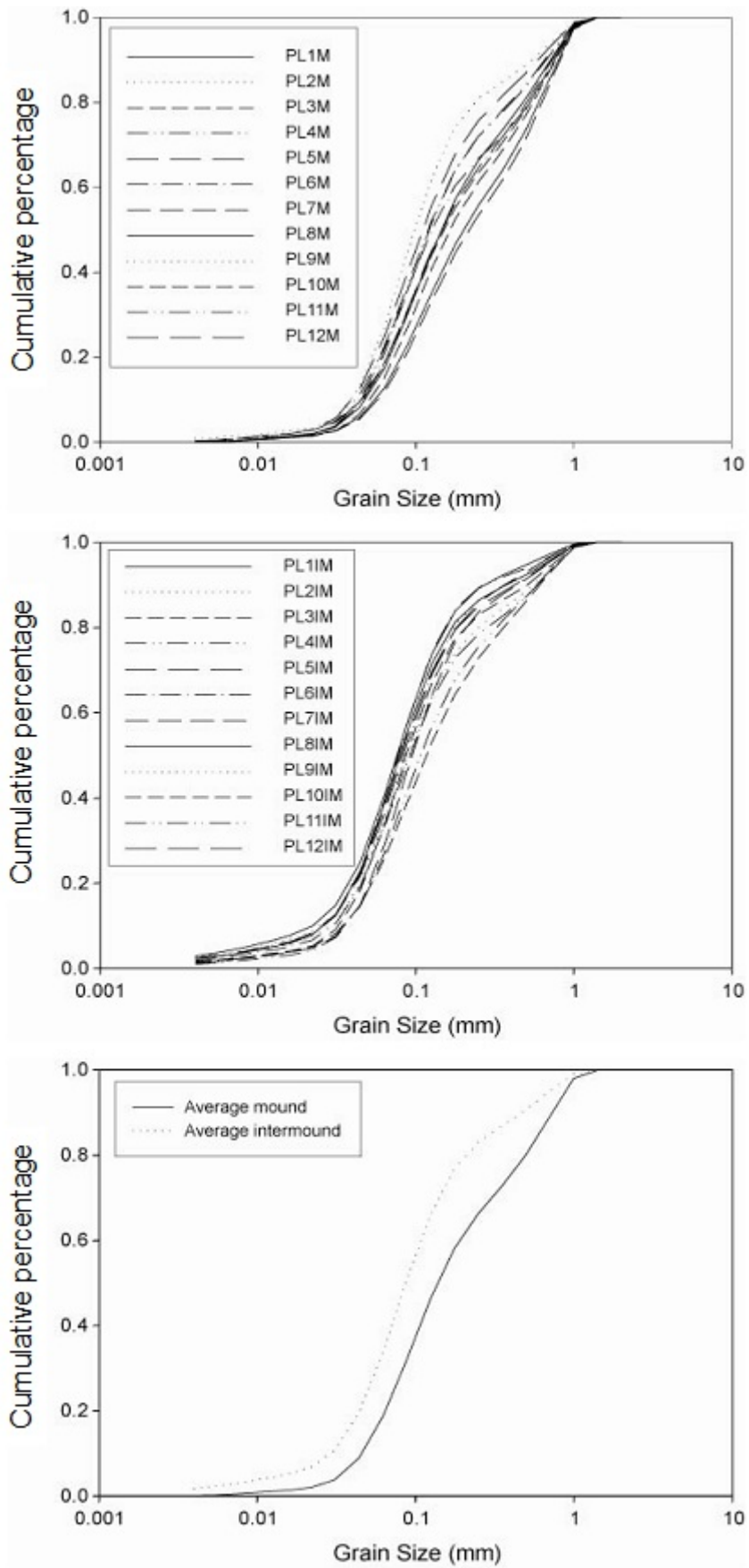
Figure 10. (continued) Cumulative grain size distribution plot for Placitas 1.

Sediment Flux

Comparisons of modeled sediment flux were made between a control hillslope with one shrub present and various scenarios with a second shrub present in differing locations. The hillslope plot is 10m x 10m and it has a gradient of 4°. If we consider the surface of the hillslope to be on a Cartesian plane with X and Y axes, where the Z axis represents elevation, the control shrub is located at (3, 3). Sediment flux was measured at a distance of 2 m above the bottom of the hillslope (i.e. 1 m in front of the center of the control shrub). While holding the control shrub constant, a second shrub is moved along the same X axis with Y coordinates of 8, 6, and 4. Similarly, simulations were done for a shrub along the same Y axis with X coordinates of 8, 6, and 4. Lastly a shrub was moved
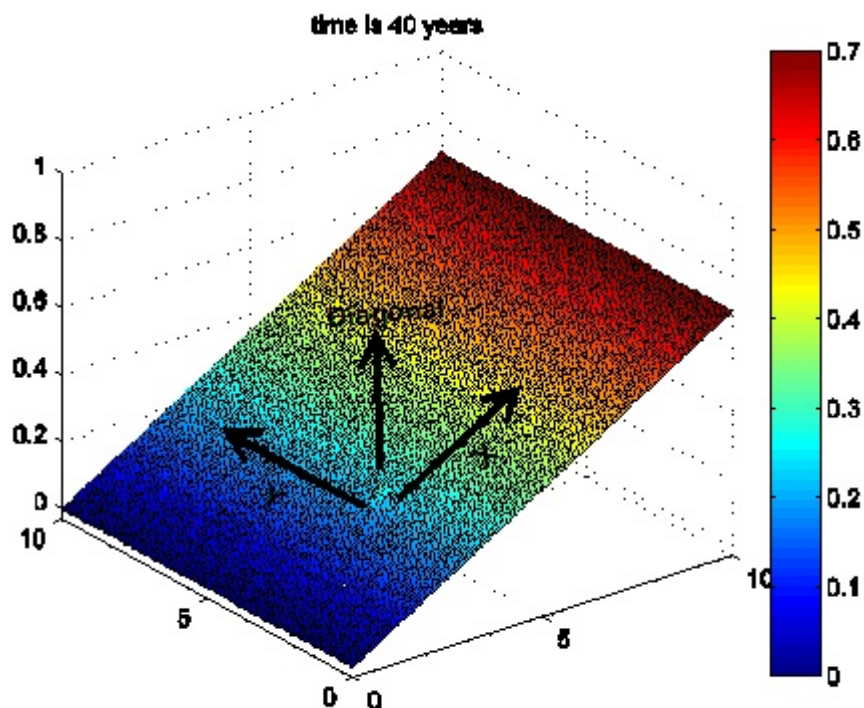
Figure 11. Definition diagram showing the three transects that a second shrub is moved along. The shrub in the lower right hand corner of the hillslope (3, 3) remains constant for comparisons between the different scenarios. The hillslope gradient is 4°; the diffusivity and transport coefficients are 0.0004 and 0.005, respectively. The mound beneath the control shrub is seen here right before the death of the shrub at 40 years.

up the hillslope in a diagonal transect with results recorded at locations (4, 4), (5, 5), (6, 6), and (7, 7) (Figure 11).

The largest effect on sediment flux was in any scenario where the second shrub was located along the same X-axis transect (Figure 12). Intuition suggests that the closer a shrub is to a flux boundary, the larger effect a shrub will have on sediment flux. Since the largest effect on sediment flux is observed where two shrubs are equidistant from the flux boundary, our intuition is confirmed. In the case where the second shrub was located behind the control shrub (both vertically and diagonally), sediment flux was not affected until the second shrub was no farther away than one meter up slope from the control shrub, i.e. at (4, 4) and (4, 3) (Figures 13 and 14).
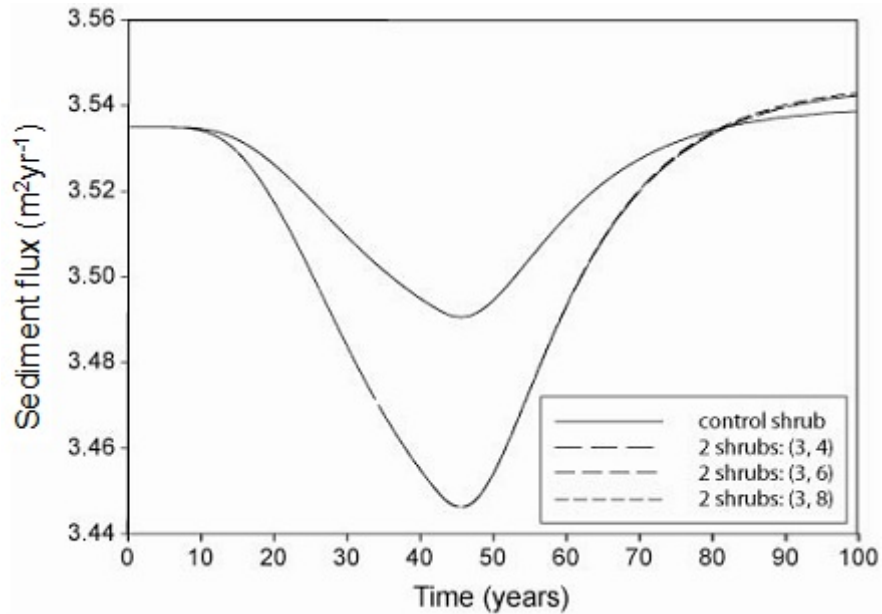
Figure 12. Plot of sediment flux versus time for scenarios involving moving a second shrub along the same X transect as the control shrub. Simulations are run for a second shrub with Y-coordinates of 4, 6, and 8. The simulation runs for 100 years, with shrub death occurring after 40 years. Hillslope gradient, D, and K are the same as in Figure 11.
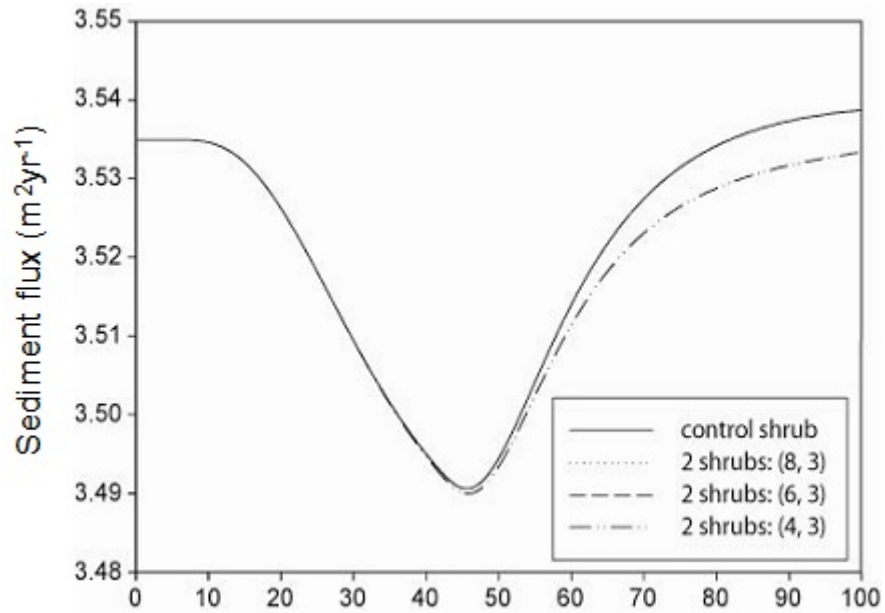
Figure 13. Plot of sediment flux versus time for scenarios involving moving a second shrub along the same Y transect as the control shrub. Simulations are run for a second shrub with X-coordinates of 4, 6, and 8. The simulation runs for 100 years, with shrub death occurring after 40 years. Hillslope gradient, D, and K are the same as in Figure 11.
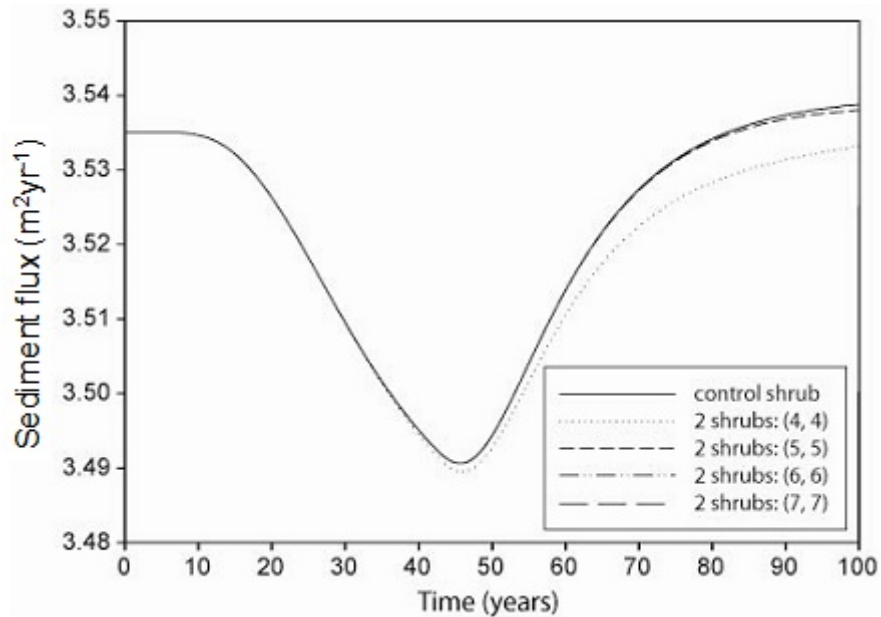
Figure 14. Plot of sediment flux versus time for scenarios involving moving a second shrub diagonally from the control shrub. Simulations are run for a second shrub located at (4, 4), (5, 5), (6, 6), and (7, 7). The simulation runs for 100 years, with shrub death occurring after 40 years. Hillslope gradient, D, and K are the same as in Figure 11.

Sediment flux was calculated after moving the second shrub along the X = 4 transect at locations of (4, 3), (4, 4), and (4, 8) (Figure 15). Sediment flux across the boundary did not change for any of the scenarios where the shrub was located along X = 4. Evidently, the interaction of two shrubs in close proximity competing for sediment is less important for hillslope sediment flux than the presence and location of a shrub and its associated mound.

Figure 15. Plot of sediment flux versus time for three scenarios where a second shrub is moved along the X = 4 transect with Y-coordinates of 3, 4, and 8. The control shrub at (3, 3) is present in all of these simulations. All three scenarios have the same change in sediment flux, indicating that the interactions between shrubs in close proximity to one another does not play an important tole in modulating sediment flux. The simulation runs for 100 years, with shrub death occurring after 40 years. Hillslope gradient, D, and K are the same as in Figure 11.
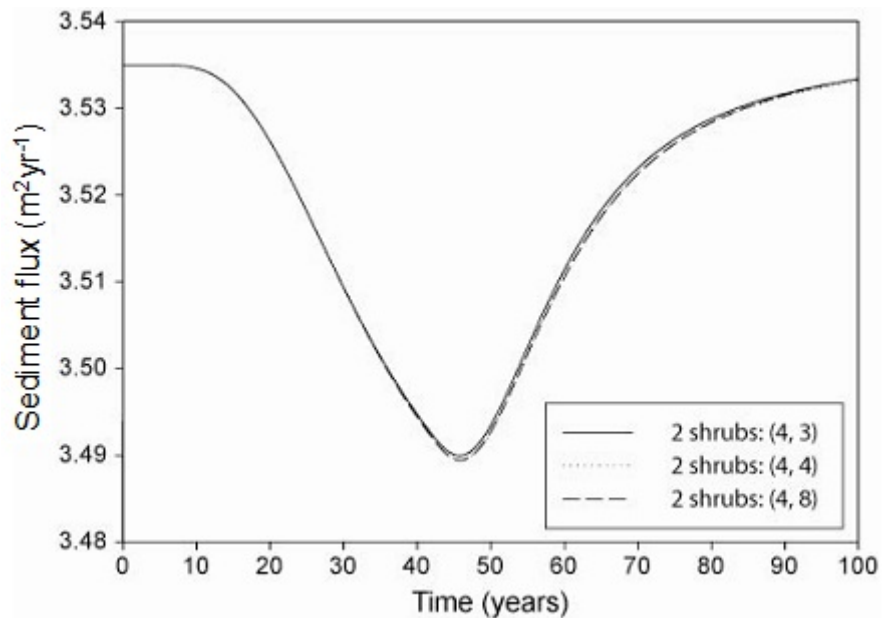
A change in sediment flux from the control scenario involving a single shrub is only seen when the second shrub is within one meter upslope. A question that remains is whether this decrease in downslope sediment flux is expressed as diminished mound sizes beneath shrubs farther downslope. In other words, do upslope mounds prevent

downslope mounds from growing as large as they otherwise would by cutting off upslope

sediment supply.

Two mounds were simulated and the sizes of the mounds were compared to see if

the downslope mound was smaller than the upslope mound (Figure 16). Whereas the

volume of two sediment mounds growing in close proximity to one another are
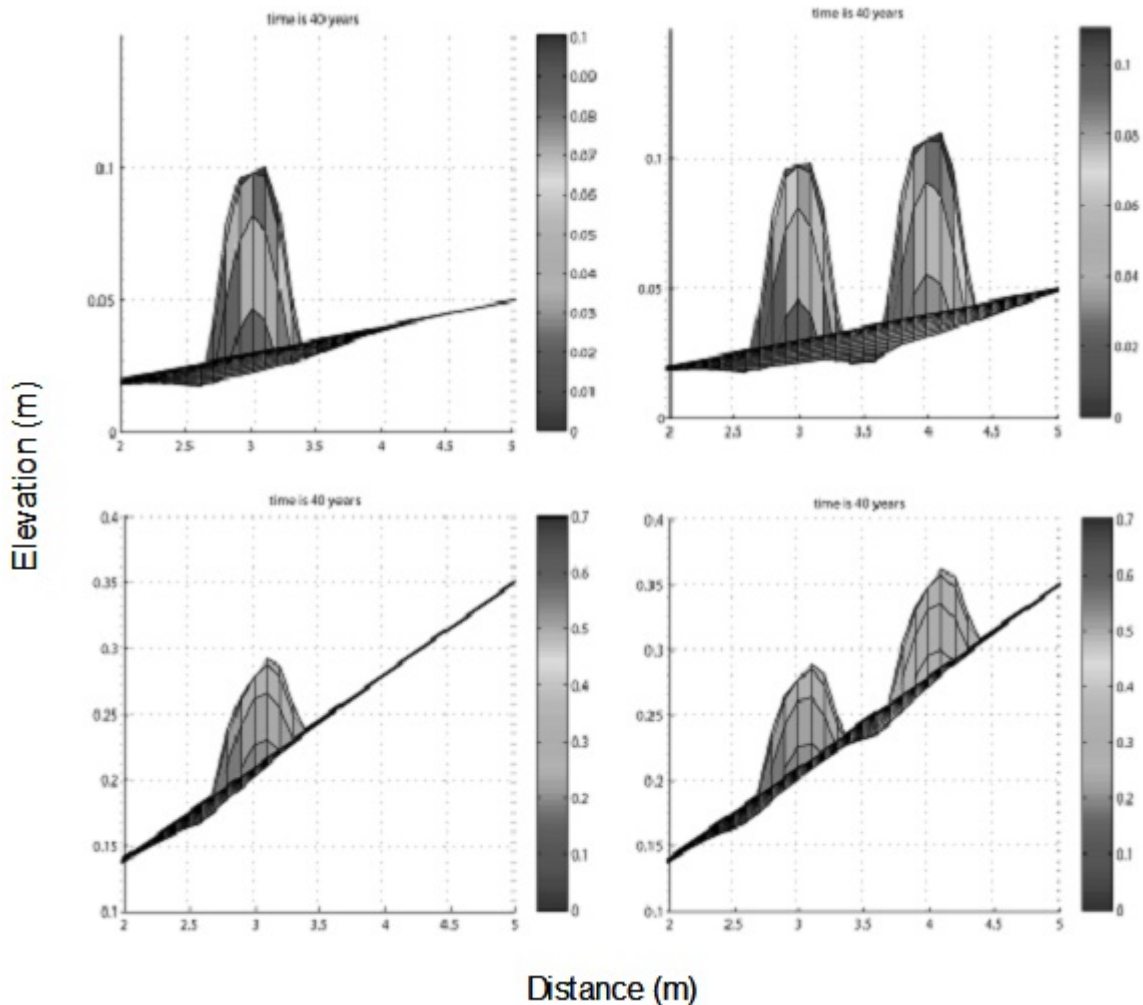
Figure 16. Comparisons of microtopography for simulated mounds with varying hillslope gradients. Whereas mound sizes are the same for one and two shrub scenarios, microtopography changes with the addition of a second shrub, as well as with increasing gradient. As hillslope gradient increases, downslope sediment flux increases. Thus, the "moat" that forms around a mound is subdued on the upslope side of mounds on a steeper hillslope (bottom row). For the hillslope with lower gradient (top row), notice the more pronounced moat on the upslope side as well as the larger divot between shrubs (top right). The simulations run until peak shrub growth at 40 years. D and K values are the same as Figure 11. Hillslope gradients are $0.6°$ and $4°$ for the left and right columns, respectively.

essentially the same as would be expected if the two mounds grew farther apart, an interesting microtopography develops around the two mounds. In the portion of soil that is not protected by the two shrub canopies (26 cm wide), a divot forms. This depression forms as upslope sediment that would normally have replaced sediment transported downslope is held in storage beneath upslope shrubs. Despite this change in microtopography, there is no difference in sediment flux between a scenario where a second shrub is directly upslope of another shrub and a scenario where the upslope shrub is farther away horizontally (i.e. Figure 15). Evidently, the change in sediment flux with each increasing shrub is additive and insensitive to interactions between shrubs.

Over a 100 year simulation, sediment flux is only significantly affected when a shrub is within one or two meters of the flux boundary that transport is measured across (Figure 17).

After breaking up our surveyed hillslope into 1.5 m increments, I find that for a 20m x 20m plot, there are about 20 shrubs located within 1.5 m of any imaginary transect. For our modeled hillslope with dimensions 10m x 10m, sediment flux is simulated with ten shrubs located in a horizontal line 1.5 m upslope of a flux boundary (Figure 18). The decrease in sediment flux associated with one shrub is amplified with the additional shrubs. Moreover, after the shrubs die, sediment flux is higher than background levels than the one-shrub scenario.
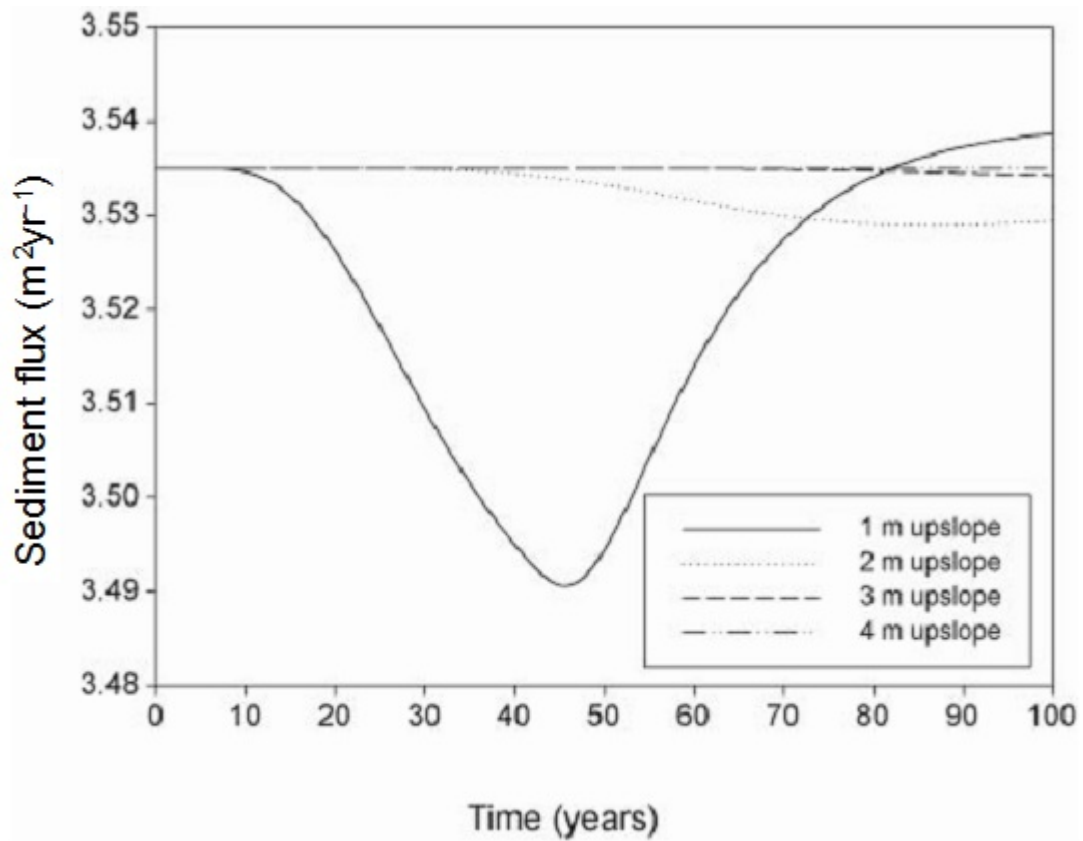
Figure 17. Plot of sediment flux versus time. Sediment flux is measured across a boundary at X = 2 for only one shrub on a hillslope. Simulations are run for scenarios where the shrub is located with X-positions of 3, 4, 5, and 6. Noticeable decreases in sediment flux only occur when a shrub is located one or two meters above X = 2. The simulation runs for 100 years, with shrub death at 40 years. Hillslope gradient, *D*, and *K* are the same as in Figure 11.
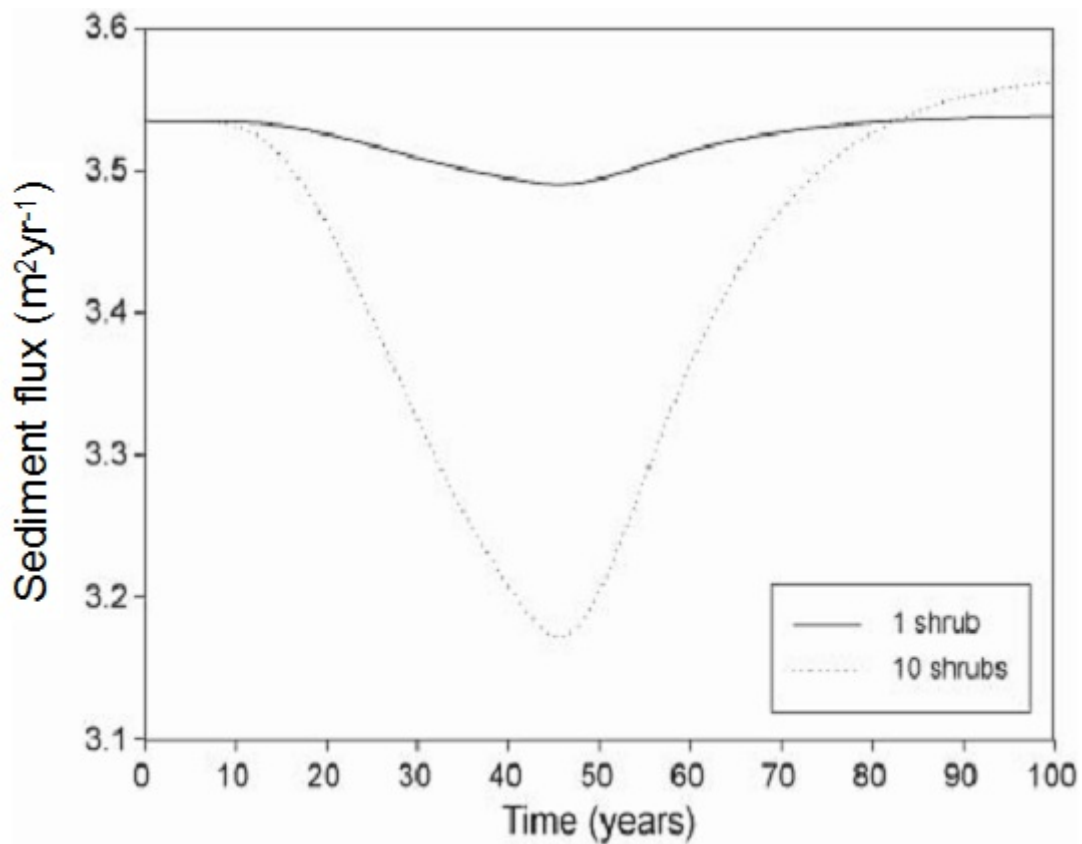
Figure 18. Plot of sediment flux versus time for two shrub population scenarios. Ten shrubs located 1.5 m upslope of the flux boundary with even 1 m spacing between the centers of each shrub is compared against a scenario with only one shrub located along the same X-transect. Note that the effects of decreased sediment flux during mound growth and increased flux after shrub death is amplified for the 10 shrub scenario. The simulation runs for 100 years, with shrub death at 40 years. Hillslope gradient, *D*, and *K* are the same as in Figure 11.

CHAPTER IV

DISCUSSION

Rainsplash transport leads to mound development on sparsely vegetated desert hillslopes due to the protection that shrub canopies provide for the soil beneath them. On the spatial scale of an individual mound, sediment grains are expected to be finer beneath shrubs than in intermound areas due to preferential splash of sand sized grains (Abrahams et al., 1995). In contrast, mounds at Arrowhead Well 1, Arrowhead Well 2, and Placitas 1 show finer sediment located in intermound samples compared to the mound samples. These results are, however, consistent with the work of Leguedois et al. (2005), who show that for various soil types, grains with the largest splash distances occur within a grain size range of 0.1 - 1.0 mm. This is the range over which our soil samples have the largest grain fraction, although many samples from beneath shrubs at our field sites are on the finer side of that range. Furthermore, Leguedois et al. show shorter splash distances for grains of approximately 0.01 mm. Our soil samples beneath mounds are depleted in this grain fraction, although at our field sites there is very little sediment that fine.

Insight from Taube et al. (2009) suggests two possible explanations for coarser grain fractions in mounds than in intermound areas. First, smaller sized grains tend to clump into larger aggregates of grains when they become trapped in the corona of a splashed rain drop. When this clumping occurs, fine grained sediment acts physically like a single large grain, thereby reducing its splash distance. Therefore, grains that are

splashed into mounds could represent the grain fraction that is small enough to be splashed longer distances, but not the finer sands that clump during raindrop impact.

Secondly, high speed imaging reveals that as grain size of sediment decreases, the splash ejection angle increases (Taube et al., 2009). For coarser sands, grains are ejected by a momentum transfer from grain-to-grain collisions at a relatively low angle. In contrast, finer sands and silt are ejected at higher angles, and consequently have farther splash distances. Again, this size fraction could represent the grains that are deposited beneath shrubs, whereas the finer material that clumps and acts as a large grain will travel with a lower trajectory and smaller splash distance.

As mounds develop and grow on a hillslope, they reduce downslope drift of sediment and nutrients. Sediment that would have been stored in a given mound is stored in mounds farther upslope. Consequently, upslope intermound areas do not replenish the sediment that they contribute to downslope transport because upslope sediment is stored in mounds. Therefore upslope intermound areas continue to decrease elevation as more sediment is transported than deposited in those areas. This can be observed in Figure 16 where a characteristic microtopography develops between two shrubs located one meter apart along the same X transect. In contrast to the one shrub scenario, a small depression develops between the two shrubs as sediment removed form the intermound area and stored in the downslope mound is not replaced by the sediment that is being stored in the upslope mound. The downslope mound is not limited in sediment due to storage in upslope mounds, but intermound spaces do experience reduced sediment input.

Furthermore, it is evident that as the hillslope angle increases, the microtopography between shrubs is subdued (Figure 16). As slope increases, downslope drift of grains with each splash increases, so whereas fewer grains are being transported downslope because of upslope storage, the grains that are splashed are more effectively transported to areas where sediment has been removed, thereby decreasing the divergence in intermound areas and slowing the rate of local hillslope evolution. This effect can also be seen between two shrubs that are located next to each other at the same x position upslope but separated one meter apart along the y axis. As hillslope angle increases and downslope sediment drift increases, the depression between the two shrubs begins to disappear.

Over the time scales modeled, this interaction between shrubs is probably insignificant for shrubs that are located more than one or two meters away from each other. Figures 13 and 14 show that sediment flux one meter downslope of a shrub is not affected until a second shrub is within one meter upslope. This holds true whether the second shrub is directly upslope from a shrub or slightly off to one side. Also, because sediment flux is nearly identical for scenarios where a second shrub is located one meter upslope, regardless of how far away the two shrubs are laterally, it appears that interplay between two mounds (or more) does not significantly affect changes in sediment flux. Rather, it is just the presence of a mound that will affect sediment flux.

When a shrub dies and canopy cover is removed, the underlying sediment and nutrients are now available for downslope transport. Within the 100 years of modeled mound development, no significant decrease in sediment flux is felt any farther than two

meters upslope from a given flux boundary (Figure 17). In other words, 60 years after the death of a shrub, sediment previously stored in a mound does not appear to travel farther than two meters. Evidently, rainsplash transport alone is inefficient in moving sediment, and by association, any nutrients transported along with sediment, very far over the modeled time scales relative to wind and overland flow.

Because sediment flux is only significantly affected by the upslope distance from a mound to a flux boundary, and not by the proximity of that shrub to other shrubs, it can be assumed that changes in sediment flux due to new shrubs growing is an additive process. Therefore, at any given point on a hillslope, changes in sediment flux with time can be simply described by the number of shrubs that are close enough upslope to matter. For the hillslopes modeled here, as well as those surveyed, with gradients of around $4°$, that upslope distance is around 1.5-2 meters. However, with increasing slope and downslope sediment drift, the upslope distance wherein a decrease in sediment flux is noticeable probably increases as well.

At Arrowhead Well 1, there are approximately 20 shrubs along the entire 20 meter width of the survey plot that are within 1.5 meters of any given flux boundary. To a fairly good approximation, this translates to a shrub density at this site of about one shrub per square meter. However, in Figure 6 it is clear that shrubs are not uniformly distributed on a hillslope. Shrub density over a hillslope has a certain element of spatial heterogeneity that is influenced, among other things, by the spatial distribution of water resources as well as the availability of nutrients on the hillslope.

This spatial variability in a shrub population on a hillslope will lead to some areas that have lower sediment transport rates than others, thereby leading to a divergence in flux such that a hillslope with an initial uniform gradient could start to develop curvature. There will be parts of the hillslope losing sediment faster than is replaced from upslope, thus creating changes in elevation that depends on the number and arrangement of shrubs present.

Whereas the creation of a divergence in flux is true at very small time steps, the resulting topographic evolution may or may not be observed, depending on the time scale over which the spatially heterogeneous distribution of shrub persists. For instance, after one growing season, some shrubs will die, and others will take root and begin to grow. If the distribution of new shrubs is similar over the course of many generations of shrubs, then similar sediment transport rates will continue, further amplifying the changes to the land surface from the previous generations. However, if the new distribution of shrubs differs from generation to generation, areas of the hillslope that were once erosional may become depositional, and vice versa, as the divergence of flux changes.

There are several reasons why it is reasonable to assume that shrub populations will continue to grow in similar spatial patterns from generation to generation. In harsh environmental settings like arid shrublands, resources are not typically uniformly distributed throughout the hillslope. Rather, resource islands, or islands of fertility, develop around shrubs (Reynolds et al., 1999). In deserts, soil nutrient distribution is often confined to areas of shrub litter accumulation, such as the observed organic particulate matter present in mound sediment samples at Arrowhead Well 1 and Placitas

1. After a shrub dies, and sediment and nutrients from a mound are dispersed by

rainsplash, it is likely that a new shrub will grow where soil nutrients are more abundant

(i.e. near the previous mound).

Also, shrubs act as barriers to wind and water, causing material transported by

these fluids to be deposited beneath the shrub canopy (McAuliffe, 1988). Reichman

(1984) found that existing shrubs also tended to be areas of relatively high seed

concentrations. The presence of seed-producing shrubs, and their ability to trap wind-

and water-borne seeds, could potentially make areas close to existing shrubs favorable for

new seed germination and shrub recruitment, especially considering the availability of

soil nutrients around these areas. Furthermore, increased runoff in intermound areas due

to potential formation of desert pavement from rainsplash processes (Wainwright et al.,

1995) could wash seeds that settle in intermound areas downslope where they are trapped

by existing shrubs. Other factors like cooler temperatures beneath shrub canopies could

also play a role in seed germination beneath existing shrubs (Hastwell and Facelli, 2003).

Some propose that competition between shrubs leads to evenly distributed shrub

communities on desert hillslopes (Phillips and MacMahan, 1981). Toft and Fraizer

(2003) showed that a broom snakeweed population moved from aggregated young shrubs

to a more mature population that was randomly distributed within a period of 15 years.

Whereas this is consistent with the notion that competition creates uniformly distributed

shrubs, they also demonstrated that after 2-3 years, seedlings grew faster in areas where

shrubs were already present, as compared to seeds that germinated away from other

shrubs. This indicates that those seedlings may have benefitted from an area that was

already favorable for seedling growth because of the presence of shrubs (Toft and Fraizer, 2003).

One commonality in desert shrub literature is the extreme spatial and temporal variability of population density. There is evidence to suggest that shrubs create 'fertility islands' around themselves conducive to shrub recruitment, while on the other hand there is evidence that at some sites competition for resources leads to uniformly and/or randomly distributed shrub populations. Certainly more work should be done to better understand the dynamics of desert shrub populations. Nevertheless, it seems plausible that desert shrub populations can maintain similar spatial distributions for a sufficient length of time to affect hillslope topography.

CHAPTER V

CONCLUSIONS

The objective of this research was to describe the effects that rainsplash-induced sediment mounds have on hillslope sediment flux and hillslope evolution. The growth of mounds on a hillslope causes modulation in sediment flux by changing local hillslope gradient in the vicinity of a shrub. Modeling of this process over a 100 year time period suggests that hillslope gradient is affected within two meters of a shrub as sediment is transported downslope without being replaced by sediment that is stored in the upslope mound. This divergence in sediment flux leads to a decrease in hillslope gradient, and thus a decrease in downslope sediment transport. Similarly, sediment flux locally will increase, potentially to rates higher than before mound development, after a shrub dies due to the increased hillslope gradient of the mound. Thus, mound development was shown to cause variations in sediment transport within two meters downslope of a shrub. Sediment flux continues to modulate for decades after a shrub dies (60 years or more).

Furthermore, mound formation on desert hillslopes was found to prevent sediment, and by extension nutrients carried within sediment, from being transported downslope to other shrubs. This upslope storage of sediment and nutrients leads to variations in hillslope microtopography in proximity to mounds, and may also play a role in the development of so-called resource islands in desert ecosystems.

Modulations in sediment flux resulting from mound development could lead to changes in hillslope curvature provided that a shrub population is not uniformly distributed over a hillslope. However, uncertainties remain concerning the implications for hillslope evolution on century to millennial timescales. Primarily, the question remains as to whether a shrub population will maintain a particular distribution long enough for significant changes in hillslope topography to develop. It is also unclear how long a shrub community needs to persist in order to cause such topographic changes.

It is apparent from this study that rainsplash processes coupled with a shrub population will cause localized topographic variations on desert hillslopes. A better understanding of desert shrub ecology and population dynamics will strengthen our knowledge of the spatial and temporal scales over which these modulations in sediment flux will lead to significant topographic evolution.

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BIOGRAPHICAL SKETCH

Andrew Roberts was born in Griffin, Georgia to Randy and Nancy Roberts. Together, he and his twin brother embarked on a campaign of global domination. This journey was abandoned by the time he started school. Growing up he found enjoyment in starting collections and never finishing them (stamps, leaves, spoons, baseball cards, etc...), playing soccer, and learning an instrument very few people have ever heard of, the euphonium. Whereas his older brother was an Eagle Scout, Andrew quit scouting at the age of 11.

In high school, Andrew warmed the bench on his varsity soccer team, but redeemed himself by excelling in the band, where he was among the best euphonium players in the state of Georgia. Trust him, this is way cooler than it sounds. Andrew starred in his school's production of the one-act play, *The Swimmer*, in which he held the title role because of his booming voice despite having no real talent for acting.

In the Fall of 2004, he enrolled at Furman University in Greenville, SC. It was here, nestled 30 miles south of the southern Appalachians that Andrew fell in love with mountains and became a geology student. Under the direction of Weston Dripps, Andrew studied sources of nitrate to urban streams in Greenville. He was president of the Bartram Society, the student organization of Earth and Environmental Sciences named after the naturalist William Bartram. He also continued his euphonium studies, getting the opportunity his senior year to perform at Carnegie Hall in New York City. This trip to New York was an amazing experience, and also gave Andrew his first chance to hail down a cab.

Andrew began graduate studies at Vanderbilt University in the Fall of 2008 where he studied desert geomorphology with David Furbish. In his spare time, Andrew enjoys entertaining tourists outside of the Nashville saloons behind his open mandolin case.