LEAF AREA AND ROOT DENSITY MEASUREMENTS FOR USE IN COVER PERFORMANCE EVALUATIONS ON SEMI-ARID RECLAIMED MINE LANDS[1]

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Abstract. Evapotranspiration (store and release) soil covers have been proposed as a means to limit acid mine drainage. Soil water balance models, like UNSAT-H are commonly used to assess the effectiveness of store and release covers. Plant-related attributes are required as inputs to these models. In particular, UNSAT-H requires leaf area index (LAI) and root length density (RLD) inputs. Published LAI and RLD data are generally lacking for semi-arid plant communities. To resolve this data gap, we collected leaf area and root density measurements in native and reclaimed shrub-grassland communities in southwestern New Mexico. Leaf area indices were determined using digital image analysis of harvested leaves at the end of the growing season. These data were used to estimate peak LAI and develop an annual LAI distribution. The average LAI ranged from 0.29 in reclaimed plant communities to 0.42 in native shrub-grasslands. LAI values for the reclaimed site did not correspond to soil cover thickness, which ranged from 23 to 62 cm. However, higher LAI values were typically associated with plots with higher amounts of shrub cover. Preceding drought and heavy grazing probably affected the LAI data in both native and reclaimed areas. Root density was measured in soil excavations using a grid-count method. Root density measurements indicated that nearly two-thirds of the roots occurred in the upper 20 cm of the soil in both the reclaimed and native areas. Very few roots occurred below 1.0 m. RLD was described by the quartile function 69-20-7-4 in the upper meter of soil. Preliminary water balance simulations using a 100-year climate record indicate that average drainage was less than 1 percent of mean annual precipitation when the measured LAI and RLD functions were applied to a 60 cm thick cover.

Additional Key Words: leaf area index, root length density, soil cover, soil water balance model, UNSAT-H

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Introduction

Evapotranspiration (ET) soil covers have been proposed as a means to limit acid mine drainage, particularly in arid and semi-arid environments. The design and performance of an ET cover depends on a rigorous analysis of numerous variables that affect the ability of the cover soil to store and release infiltrated water. Soil water balance models, like UNSAT-H (Fayer, 2000) are commonly used to optimize and assess the effectiveness of ET cover systems.

Plant-related attributes are required as inputs to soil water balance models because the performance of ET covers primarily rely upon transpiration of water by plants to remove water from the profile. Specifically, UNSAT-H requires leaf area index (LAI) and root length density (RLD) inputs. While plants are actively growing, transpiration is the dominant mode of water loss from the soil profile, even with sparse vegetation (Hillel, 1998). The RLD function allocates water removal from the model domain.

LAI is defined as the one-sided green foliage area-per-ground area (Scurlock et al., 2001; Campbell and Norman, 1998). Published LAI values for semi-arid plant communities are generally lacking. The available LAI data come from studies that used indirect methods (allometry, point frames and light interception meters) to collect leaf area information. Indirect measuring techniques demonstrate considerable variability because the methods have difficulty with the discontinuous canopy and variable amounts of standing dead material typical of semi-arid plant communities (Groeneveld, 1997; Barclay, 2000).

Scurlock et al. (2001) reviewed worldwide historical leaf area studies and reported mean LAI values for deserts (1.31 $\pm$ 0.85), grasslands (2.5 $\pm$ 2.98), and shrublands (2.08 $\pm$ 1.58). Light interception measurements using light meters have produced a wide range of LAI values for semi-arid plant communities in Arizona and Colorado including desert scrub (0.93), open oak woodland (1.76), desert grassland (1.58), and grass steppe (0.5) (Whittaker and Niering, 1975; Welles and Norman, 1991). Light interception techniques tend to include non-photosynthetic plant organs (stems) in their estimate of LAI. Point frame methods employed by Clark and Seyfried (2001) in Idaho sagebrush communities found LAI values ranging from 0.03 to 1.1. Asner (1998) reported LAI's in New Mexico using allometry ranging from 0.8 to 3.8 for a black grama (*Bouteloua eriopoda*) grassland; 0.8 to 1.9 for a shrub steppe (creosote [*Larrea tridentata*] and black grama); and 0.9 to 3.9 for a mesquite (*Prosopis glandulosa*) scrubland.

Knowledge of the distribution of roots in unsaturated soils is important for predicting soil-water relations, but quantitative data are generally absent in scientific literature. Jackson et al. (1996) indicated that 83 percent of rootmass occurred in the upper 30 cm of soil in temperate grasslands compared to 53 percent in deserts. In a study in central New Mexico, semi-arid grassland had 63 percent of the root mass in the upper 25 cm (Peace et al., 2004). Similar root distributions for arid and semi-arid grasslands throughout the world have been reported (Lee and Lauenroth, 1994; Moorhead et al., 1989; Rundel and Nobel, 1991; Schulze et al., 1996; and Sims and Singh, 1978).

This investigation sought to determine leaf area and root distributions in native and reclaimed shrub-grassland communities in southwestern New Mexico. Using the peak LAI data, an annual LAI distribution was developed for use in the model. These plant attributes were then used as parameters in the soil water model to assess the effectiveness of a store and release cover to limit acid mine drainage. Simple comparisons (t-test and correlation) were also conducted to understand the differences among LAI and root density in the two plant communities.

Environmental Setting

The study area sits along the continental divide in southwestern New Mexico at elevations ranging from 1,825 to 1,980 m (6,000 to 6,500 feet) above sea level. The climate is warm and dry with a mean annual precipitation (MAP) of 400 mm (16 inches) and a mean annual temperature near 10°C (50°F). Precipitation falls mainly in short, intense thunderstorms between July and October, and winter precipitation is typically less intense rain showers or snow. Native soils are loamy-skeletal, clayey-skeletal, and fine families of Aridic Haplustalfs formed in residuum from late Tertiary and Quaternary conglomerates. The soils are very deep, non-saline, non-sodic, medium- to fine-textured, and calcareous in the lower solum and substratum.

Leaf area and root density data were derived from a native piedmont scrub savanna plant community and a 20 year-old revegetated tailing repository dominated by warm-season grasses with a nominal 60 cm (2 feet) thick cover. The original seed mix for the repository did not have a shrub component, though shrubs are slowly colonizing the area. Cover soils in the revegetated area are coarse- to moderately coarse-textured (Munk et al., 2006). Vegetation plots were located in upland locations to remove confounding variables associated with run-on. Historically, the sample sites were passively managed for cattle production with year-long grazing. Grazing pressure is relatively low in the native area, but was moderate to heavy on the tailing repository. Despite near normal precipitation in 2004, the region had been subject to a prolonged drought for about five years prior. Thus, the plant communities we measured may not have fully reflected the long-term average condition.

Methods

Leaf Area Index

Sample sites were selected within the two study areas using a random systematic sampling procedure employing a transect/quadrat system. Quantitative vegetation measurements and plant tissue collection were taken in 0.25 m^2 quadrats placed at predetermined intervals along a 30-m transect in randomly chosen 15.3 m^2 (50 ft^2) plots. The transect was in a dog-leg configuration to avoid confrontment with drill seeding patterns. The dog-leg ensures that at least part of the transect is perpendicular to the pattern. A total of eight plots (32 quadrats) were sampled in the native scrub plant community, and seven plots (16 quadrats) were sampled at the reclaimed plant community. The soil cover in the tailing repository ranged from 38 to 63 cm (15 to 25 in) thick.

Fieldwork was conducted in the early fall of 2004 prior to the first killing frost. Visual estimates of canopy cover, basal cover, surface litter, rock fragments, and bare soil were made for all quadrats prior to clipping. Each species within the vertical projection of the quadrat was clipped to within about 0.5 cm of the ground surface and placed into separate plastic bags.

In the lab, plant samples were pressed to preserve the materials prior to analysis. After drying, photosynthetic leaves were separated from tissues that have limited ability to photosynthesize or transpire (e.g., stems, flowers, and leaf tissue representing last year’s growth) and arranged on white paper to minimize overlap. Black-and-white digital images were taken of each sample. Each picture was backlit to reduce shadows and glare to provide a clear image for digital analysis. Standard scales were photographed with each plant sample to calibrate the image size and allow the estimation of any distortion errors. The digital images were processed using commercially available software to improve contrast and the image was reduced to a representative two-color (1-bit) bitmap. The number of pixels corresponding to the standard scales and leaf area were determined using the software's histogram function. LAI was then calculated for each sample and totaled for each quadrat.

Root Length Density

Root density was determined using the profile wall method, whereby the roots are counted on a freshly excavated soil profile (Moore and West, 1973; Böhm, 1979; Heitschmidt et al., 1988; Mackie-Dawson and Atkinson 1991; and Montaña et al., 1995). Five trenches were excavated and the soil was described by a Certified Professional Soil Scientist. The vertical pit wall was gently cleaned with a soft brush to expose the roots to a depth of approximately 1 to 1.5 m. A 1-m^2 wire frame divided into a 10 cm^2 grid was then attached to the pit face and the roots within each grid cell were counted and mapped on field sheets. Roots were also described and classified by size (Soil Survey Staff, 1983). In total, root counts were made on 13 profiles in three native and two reclaimed sites. Data were analyzed and the RLD function was optimized to fit the normalized root density data.

Results

Leaf Area

Peak LAI values were calculated by averaging individual quadrat data for each study area (Table 1). The native vegetation had an average LAI of 0.42 which was significantly higher ($p< 0.05$) than the reclaimed plant community that had an average LAI of 0.29. However, there was no significant difference in average canopy cover between native and repository sites (Table 1). Shrub densities were higher in the native area (0.46 shrubs/m^2) than in the reclaimed area (0.02 shrubs/m^2), and no shrubs were encountered in the sample quadrats in the reclaimed area. This structural difference between native and reclaimed sites probably accounts for the significant difference observed in LAI. Quadrats in the native plant community that encountered shrubs typically had LAI values greater than 0.5. No relationships were observed between individual quadrat LAI and canopy cover or between LAI and cover thickness within the reclaimed area.

Within the context of this study, the LAI measurements were affected by a number of factors. Sample preparation and pressing ultimately resulted in some degree of leaf overlap, desiccation, and folding. Structural analysis of a subset of images determined that leaf overlap resulted in underestimation of LAI by 10 to 20 percent. Underestimation was most pronounced in the higher leaf area samples. No corrections were applied to account for the shrinkage and folding (curling of cylindrical leaves). Many plants have other herbaceous photosynthetic tissues (e.g., green twigs and grass stems) that have the capacity to transpire water, but we excluded these in the interest of conservatism for the model. These factors likely reduced the total leaf area to a varying degrees depending on the species and size of sample.

This investigation sought to determine the peak leaf area that corresponds to the highest transpiration capacity of the reclaimed plant community. However, UNSAT-H uses daily LAI values to simulate changes in active photosynthetic tissue throughout the year. Thus, annual LAI distribution functions were developed based on ecological considerations and using the measured peak LAI values for the two sites (Fig. 1). The specified plant growth season is between March and early October when the average temperature is above 4.4°C (40°F). The abrupt increase in July corresponds to the typical arrival of the summer rains.

Table 1. LAI and corresponding canopy cover for native and reclaimed plant communities in southwestern New Mexico.

Study Area /Plot	LAI				Canopy Cover % (CC)			
	Quadrat				Quadrat			
	A	B	C	D	A	B	C	D
Reclaimed Area								
1	0.11	0.18	--	--	13	23	--	--
2	0.37	0.32	0.51	--	27	39	47	--
3	0.25	0.32	--	--	25	29	--	--
4	0.11	0.12	0.48	--	22	16	80	--
5	0.34	0.33	--	--	90	66	--	--
6	0.13	0.20	--	--	18	20	--	--
7	0.56	--[a]	--	--	85	16	--	--
	Average LAI 0.29 ± 0.15				Average CC 38.4 ± 26.7			
Native Area								
1	0.13	0.20	0.12	0.89	6	49	14	97
2	0.50	0.32	0.37	0.72	35	30	25	28
3	0.20	1.23	0.65	0.32	8	100	100	15
4	1.23	0.40	0.33	0.54	85	30	28	95
5	0.46	0.40	0.17	0.32	43	62	15	24
6	0.47	0.20	0.29	0.30	38	20	25	37
7	0.46	0.28	0.38	0.27	40	27	38	25
8	0.45	0.20	0.28	0.33	82	30	33	37
	Average LAI 0.42 ± 0.27				Average CC 41.3 ± 16.5			

[a] sample incomplete

Root Distribution

Characteristics of the root density study sites are listed in Table 2. In general, the soils were moderately deep to deep, well drained, and had moderately coarse textured surface horizons. The slopes were mostly nearly level to gently sloping, except for the RS1 site, which was strongly sloping. Canopy cover ranged from 35 to 50 percent, and vegetation immediately adjacent to the pit walls was dominantly grasses (i.e., blue grama [*Bouteloua gracilis*] with either vine mesquite [*Hilaria belangeri*] or single awn threeawn [*Aristida schiedeana]*) with scattered shrubs and forbs. As expected, the root densities were higher in the native soils compared to the reclaim sites (Table 2). Statistically significant differences in root density were limited to the upper 30 cm. The differences in root density between the native and reclaimed sites may reflect divergent soil and ecological development and past grazing management.

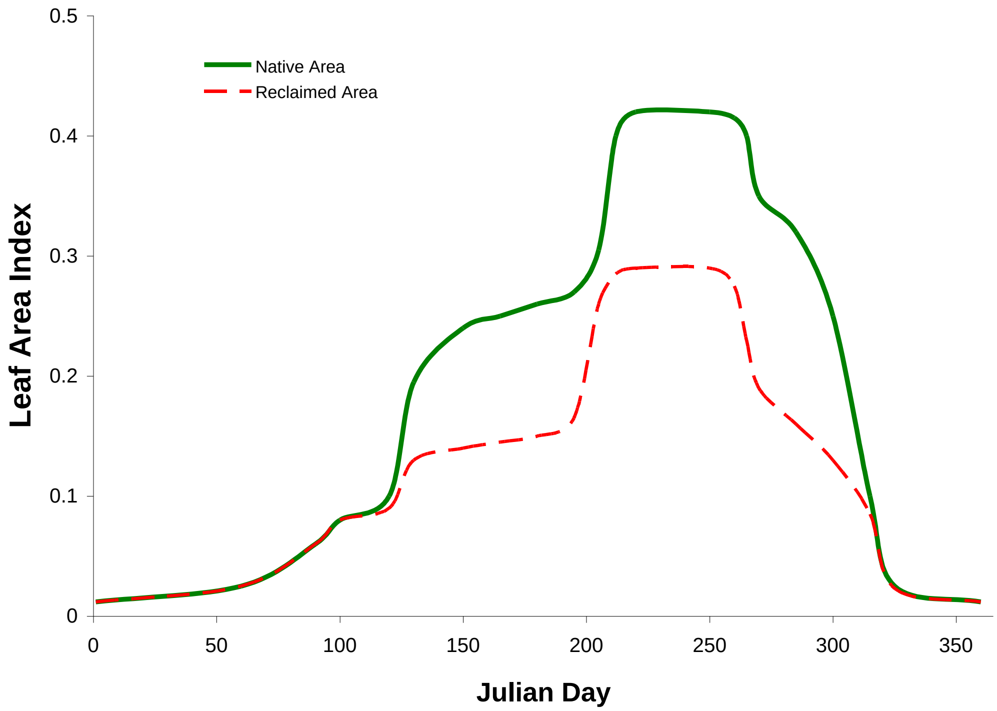

Figure 1. Annual leaf area distribution curves.

Table 2. Root density test pit site descriptions.

Trench No.	No. of Profiles	Surface Texture	Soil Depth (cm)	Slope (percent)	Canopy Cover (percent)	Average Root Density (roots/m^2)
Native						
RS1	1	Gr SL	150 +	31	40	2,389
RS2	3	Gr SL	125+	7	35 to 40	1,049
RS5	3	Gr SL	125+	9	25 to 35	1,844
Reclaim						
RS3	3	Gr SL	86	2	30 to 35	1,009
RS4	3	Gr SL	100	1	25 to 50	714

Notes: Gr SL = gravelly sandy loam

Regardless of sampling location (native or reclaimed), the roots were concentrated in the upper profile (Table 3). On average, 62 percent of the roots were in the upper 20 cm of the profile, with more than 90 percent in the upper 60 cm. The quartile distribution of roots (percent roots in each 25 cm depth interval) within the 1-m profile was estimated at 69-20-7-4. Very few roots were found below 1 m in the native scrub grassland. Very fine roots were occasionally found in tailing. Figure 2 illustrates the average cumulative profile root distribution for both the native and reclaimed areas, and the average for the study area. Although they vary in magnitude, the curves are similar for both native and reclaimed areas. Roots were mostly very fine (<1 mm), occasionally fine (1 to 2 mm), and rarely medium and coarse (2 to 10 mm), reflecting the dominance of grasses in the two areas.

Table 3. Summary of root density data from the study area.

Depth Interval (cm)	Average Root Density (roots/dm^2)			Cumulative Average Root Density (percent)
	Study Area	Native	Reclaim	
0 - 10	51.7	61.2[a]	40.5[b]	41
10 – 20	25.4	32.7[a]	16.8[b]	62
20 – 30	17.1	24.1[a]	9.1[b]	75
30 – 40	10.4	14.5	5.5	84
40 – 50	6.7	8.4	4.7	89
50 – 60	4.2	5.0	3.3	92
60 - 70	3.7	4.5	2.8	95
70 - 80	2.7	3.1	2.2	98
80 - 90	1.7	2.4	0.9	99
90 - 100	1.5	2.3	0.4	100

Notes: Depth intervals with different letters are significantly different at $p<0.05$

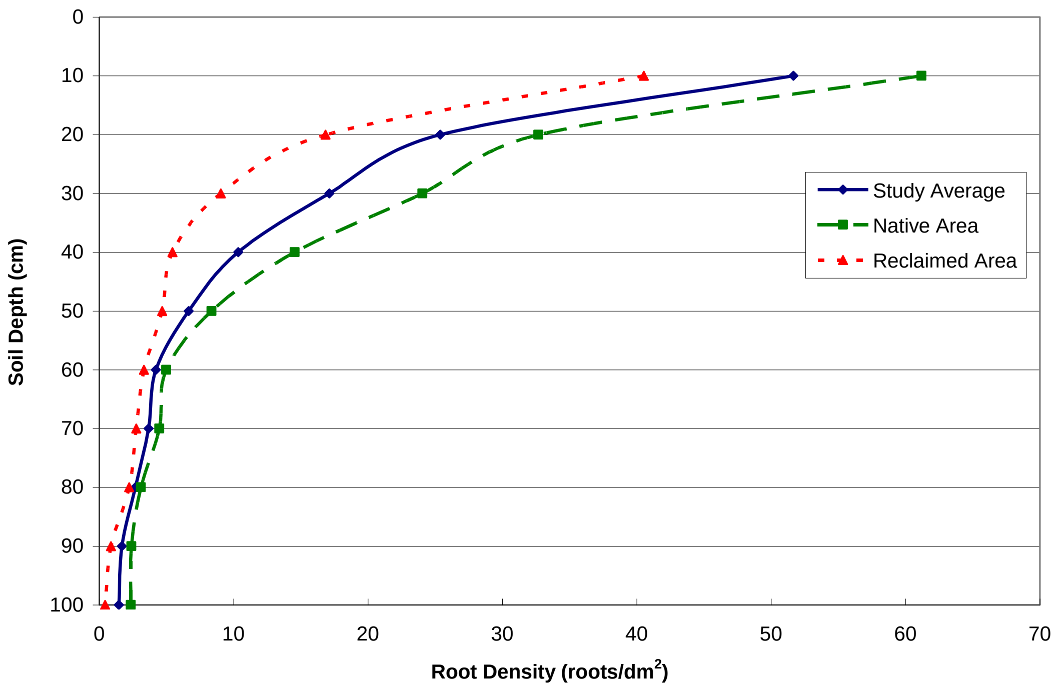

Figure 2. Average cumulative root density profiles.

In UNSAT-H, RLD is related to the depth below the surface (z) by exponential equation (1):

$$RLD = ae^{-bz} + c \qquad (1)$$

where a, b, and c are coefficients that optimize the fit to normalized root density data (Fayer, 2000). The coefficients that best describe the average root density for the study area are: a = 0.700, b = 0.060, c = 0.016. The root density curve developed in this study is illustrated on Figure 3 along with curves developed at Sandia National Labs in Albuquerque (Peace et al., 2004) and for agricultural crops (Ayers and Westcot, 1989). The curves for the semi-arid plant communities represent relatively higher proportions of the roots in the upper profile when compared to agricultural situations. This is expected as water supply limitations associated with the prevailing climatic regime of the mid-elevations in New Mexico result in the concentration of roots in the upper part of the soil profile.

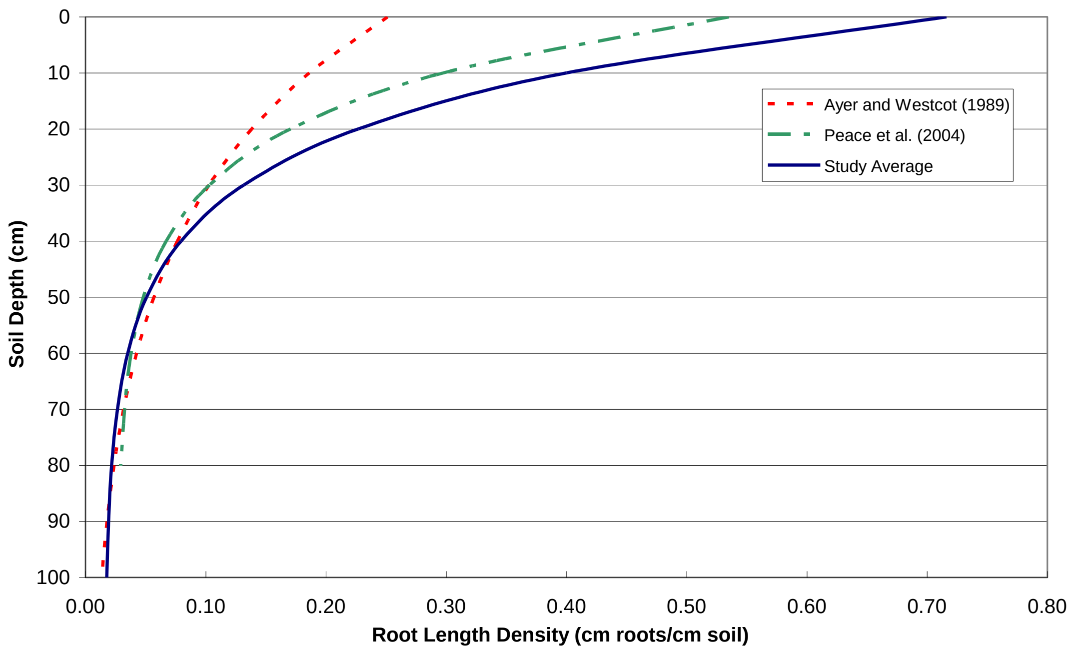

Figure 3. Comparison of study's RLD function with agricultural crops (Ayers and Westcot, 1989) and central New Mexico grasslands (Peace et al., 2004).

Long-term Soil Water Balance Simulations

Preliminary soil water balance simulations using the measured LAI and RLD functions predicted average drainage of less than 1 percent of MAP over a 100 year period for a 60 cm thick cover. Long-term average drainage decreased from 2.6 mm/yr to 1.9 mm/yr when the peak LAI was increased from 0.29 to 0.42.

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