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16. ABSTRACT

The purpose of the study was to evaluate soil treatments for their effect on establishment of wild-land shrubs without supplemental irrigation. The treatments that significantly improved growth over irrigation alone at a central California fill slope site (Contra Costa County, route 4) involved deep soil decompaction and/or compost addition. General information regarding use of water by plants and retention of water by soil or soil amendments was evaluated from literature reviews, by lab analysis and with plant water-use modeling. A method was developed to predict the plant water use and soil water availability characteristics that would allow field establishment of shrubs through dry summer conditions without supplemental irrigation. This method was then tested in different substrate and climatic conditions in three additional counties around the state (Sutter (route 70), Mono (route 395) and San Diego (I-5)). In all cases, shrubs on soil treatments including deep soil decompaction and compost incorporation grew larger than those on untreated substrates. No supplemental irrigation was used except to wet the profile once at time of planting, and even then only if ambient soil moisture was insufficient. The recommended treatment is to decompact the substrate by excavation or ripping or fracturing to three feet depth if the substrate is not already rootable, then to add an inch of compost and incorporate into the top foot (unless the area receives atmospheric deposition or contains residual soil organic matter or is in a desert environment), and then to plant containers with site-appropriate species and to cover the immediate area with two inches of wood chip mulch.

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Vic Claassen
University of California, Davis

California Department of Transportation

Disclaimer page

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Acknowledgements

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Executive Summary

Several soil or substrate treatments were tested for their effect on establishment of wild-land shrubs without supplemental irrigation. The treatments that significantly improved growth over irrigation alone at a central California fill slope site (Contra Costa County, route 4) involved deep soil decompaction and/or compost addition. General information regarding use of water by plants and retention of water by soil or soil amendments was evaluated from literature reviews, lab analysis and with plant water-use modeling. A method was developed to predict the plant water use and soil water availability characteristics that would allow field establishment of shrubs through dry summer conditions without supplemental irrigation. This method was then tested in different substrate and climatic conditions in three additional counties around the state (Sutter (route 70), Mono (route 395) and San Diego (I-5)). In all cases, shrubs on soil treatments including deep soil decompaction and compost incorporation grew larger than those on untreated substrates. No supplemental irrigation was used except to wet the profile once at time of planting, and even then only if ambient soil moisture was insufficient. The recommended treatment is to decompact the substrate by excavation or ripping or fracturing to three feet depth if the substrate is not already rootable, then to add an inch of compost and incorporate into the top foot (unless the area receives atmospheric deposition or contains residual soil organic matter or is in a desert environment), and then to plant containers with site-appropriate species and to cover the immediate area with two inches of wood chip mulch. This treatment will store adequate soil moisture for survival and growth in the dry summer season, assuming that the whole soil profile is wetted by winter rains by late spring. Only if rainfall is insufficient to wet the soil profile would a single saturating water application be needed. Coarse sandy soils with less than 10 % water holding capacity can benefit from application of a soil treatment to improve water retention. Lab data indicated that a calcined diatomaceous earth product would perform the best to

release stored moisture when the plants were water stressed (drier than -1.5 MPa, or - 15 bars), rather than when the soils were still damp. But, plant available moisture on dry, wild-land sites can generally be more readily improved by increasing rooting depth by tillage or fracturing than by incorporation of soil amendments near the soil surface. Protection against weed competition is important. Many sites had multiple growth limiting conditions, suggesting that mitigation sites with poor plant growth often require comprehensive soil treatment or regeneration and should not be expected to have a treated single missing factor that can be solved with a simple “magic bullet” amendment.

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Section #

Section 1. Project Deliverables

Contract deliverables and tasks include 1) literature review, 2) work plan for construction and monitoring of laboratory and field test plots, 3) site selection, 4) measurement water holding capacity of soils and amendments, 5) construction of a central California site, 6) construction of three additional state-wide sites, 7) monitoring of sites and 8) reports.

The Task 1 Literature Review is presented in Appendix Section B, C, and D of this report. The Task 2 Work Plan is presented in Appendix A, "Revised Work Plan Outline from January 11, 2006." The Task 2 Laboratory Test Plot (outdoor garden experiment) is described in Section 3. Task 3 Site Selection Criteria are contained in the Appendix A work plan. Task 4 Water Holding Capacity literature is reviewed in Appendix Section C, while Task 4 Laboratory Measurement of water holding capacity is presented in Section 4. Task 5 Construction of a Central California Site is described in Section 5. Construction of three Additional Sites is described in Section 6. Task 7 Site Monitoring information is included in the appropriate section for each site. This document represents Task 8, the Final Report of the project.

Section 2. Project Introduction

The California Department of Transportation is required to establish compensatory plantings to mitigate for impacts along its right-of-way. In California's arid environment, new plantings are often irrigated to insure survival. Mitigation plantings often require extensive, expensive and maintenance intensive irrigation systems to get plants established. In response to this problem, the Department developed a project to develop alternatives to conventional irrigation practices for establishment of roadside plantings. This will improve the success of mitigation plantings as required by regulatory agencies, and will help to ensure, during drought years when water resources are diverted from irrigation systems, that highway plantings will survive and continue to provide both aesthetic and functional benefits.

From a water quality standpoint, these roadsides may contribute to accelerated soil erosion and water pollution if left bare of ground cover. To ensure that the Department meets its stormwater commitment for eliminating pollution discharges, sustaining healthy vegetation on roadside slopes is critical.

The objective of this project was to develop alternatives to irrigation for establishment of roadside plantings. Our approach started with a literature review of water use by wild-land plants. We grouped the data for four generic plant types: annual grasses, perennial grasses, shrubs and trees. Generalizations for water use among these plant types were made from existing literature values and plant water use information. Plant species were selected that were appropriate for California landscapes. They were grown in large pots in a greenhouse and water use was measured under both water-stressed and well watered conditions. Basic data was generated from this experiment showing how flexible these wild-land plants can be in their water use. Experimental water use data for two shrub species was used to estimate water use for the whole summer.

The next phase of the project involved evaluation of soil moisture supply, rather than plant moisture demand. Due to the disturbed nature of the soils often found on roadsides, soil amendments are often needed to increase water holding capacity in these soils. Selected inorganic amendments and polymers were evaluated for their ability to increase the water holding capacity of soils. Demonstration plots were designed that would provide the amount of plant-available soil water storage needed as estimated by the greenhouse data. Soil amendments were used to increase the soil water resources to desired levels. These plots were monitored for growth and survival. It became apparent that broad generalizations about water use would not adequately describe California's diverse range of climates and plant types.

A more flexible way of accounting for local climate, plant size and density needed to be developed in order to insure plant survival. A second literature review of water use model parameters developed for wild-land plants was performed. Although few relevant papers were found, this method of estimating water use seemed promising. An initial exploratory experiment was set up to use meteorological methods to measure plant water use. The data from that experiment was used to develop model parameters that when placed in a plant water use model (Penman-Monteith) matched well with observed soil moisture depletion from roadside plots. In light of this success, additional meteorological methods were used to evaluate model parameters for desired wild-land roadside plants so that site specific plant water use could be estimated. The plant water use model that was developed by this project will help designers determine appropriate levels of soil treatment to ensure that constructed slopes have adequate water resources to establish plantings without relying on irrigation.

Section 3. Outdoor Garden Trials for Estimating Plant Water Use

Synopsis

This section describes an initial experiment to determine how quickly plants adjust their water use after they start to experience water stress. Information on the response time for changes in plant water use is needed to understand behavior of plants in field conditions that expose the plant to sudden or repeated water deficiencies. Plant adjustment to experimentally imposed water stress conditions occurred in less than one week. Toyon used the lowest amounts of water with little difference in transpiration between well-watered and water-stressed treatments. Coyote bush used slightly more water and had slightly more response (reduced transpiration) to water stress. Water use of well-watered grasses was much higher than for the shrubs and the response to water stress (reduced transpiration) was much greater. These findings have practical applications in that a period of water stress at the end of the propagation period may be used effectively to 'harden' plants for better survival in droughty field conditions. These data suggest that this hardening period can be relatively short, requiring less than one week for these species and growing conditions. Shrubs appear to transpire less, to grow less rapidly, and to be more conservative with water use after out-planting than grasses under the conditions of this study.

Introduction

Water stress of plants in roadside environments is a common problem especially where the capacity to provide irrigation is limited. Ideally, the amount of irrigation and the moisture capacity of the field soil should be matched to the amount of water actually used by the introduced plants. This information is rarely available, and projects usually rely on crude estimates of plant water requirements. A further complication comes from plant responses to changes in the amount of available water. Previous work indicates that some species respond rapidly to additional available moisture under low soil moisture tensions (as found in most irrigated sites) and greatly increase their water use, while other species show relatively little increase in response to high soil moisture (Garcia-Navarro et al. 2004). In this experiment we measured the response of container-grown plants to drastically reduced irrigation rates to see if the results could be used to improve design of roadside sites where minimal irrigation will be applied.

Methods

An experiment was conducted on four California native plant species, including two shrubs and two grasses, during summer 2005 in the Environmental Horticulture nursery at UC Davis. The shrub species were Toyon (*Heteromeles arbutifolia*) and coyote bush (*Baccharis pilularis*); the grasses were Purple needlegrass (*Nassella pulchra*) and Saltgrass (*Distichlis spicata*). All were purchased as nursery liners from commercial sources in spring 2005 and transplanted into 1-gallon containers filled with a soilless substrate (sand:redwood sawdust:peatmoss in a 1:1:1 ratio by volume). A total of 64 plants, 16 of each species, were placed on a bench in the outdoor nursery. The bench was designed to minimize sun exposure and heating of the potting substrate. It was constructed of plywood with 6-inch diameter holes on 15-inch centers, so that the lip of each plant container was flush with the bench surface. The sides of the bench were draped from bench top to ground with cheesecloth that was kept moist to provide evaporative cooling under the bench. The plants were arranged in a randomized complete block design (4 species X 2 irrigation treatments X 8 blocks).

All plants were watered daily to container capacity for approximately two months prior to the start of the experiment. Beginning on 12 July, the two irrigation treatments were imposed. Plants in the well-watered treatment continued to receive daily irrigation to container capacity. Irrigation was withheld from plants in the water stress treatment until they had removed the available water from the container. Those plants were then irrigated to container capacity and subjected to a new cycle of stress. The available water was determined from a moisture release curve of the substrate; the difference between moisture content at 0.6 and 40 kPa was considered plant available water. Note, however, that the moisture potentials used for this soil-less substrate are much less negative (more moist) and are not comparable to those used to define plant available moisture in a mineral soil or degraded geological substrate. The difference arises from a lower conductivity of water to the root under moisture withdrawal conditions in these organic-rich materials, which effectively imparts moisture stress under less measured moisture tension (closer to zero) compared to mineral soil materials with smaller, more connected pore structure. Daily water use of each plant in both irrigation treatments was determined gravimetrically. Treatments continued though 25 August 2005.

Plant height and diameter of the grasses and shrubs, and basal stem caliper of the shrubs, were measured periodically during the experiment. At the end of the experiment, plants were removed from the containers, separated into shoots and roots. The potting substrate was washed from roots, after which shoots and roots were dried in an oven at 70°C and weighed. Water use data were compared to daily reference evapotranspiration (ET_o) values published for the nearby Davis CIMIS weather station. Evapotranspiration for all four species was calculated based on projected area covered by the plant canopy. All data were subjected to analysis of variance, and significantly different mean values were distinguished using Duncan's honestly significant difference test.

Results and Discussion

Evapotranspiration for all four species was considerably less than ET_o (reference evapotranspiration estimated from green, irrigated, mowed grass) when based on projected area covered by the plant canopy (Fig. 1). Water stress is indicated by increasing distance between the well-watered (solid; black) and water stressed (open; white) symbols. Symbols are close together in the first days after start of the experiment (starting at the left axis), but soon become farther apart as water stressed plants reduce usage. Evapotranspiration of water-stressed plants became less than that of well-watered plants after about one week of the start of the low-irrigation treatments. The difference in water use

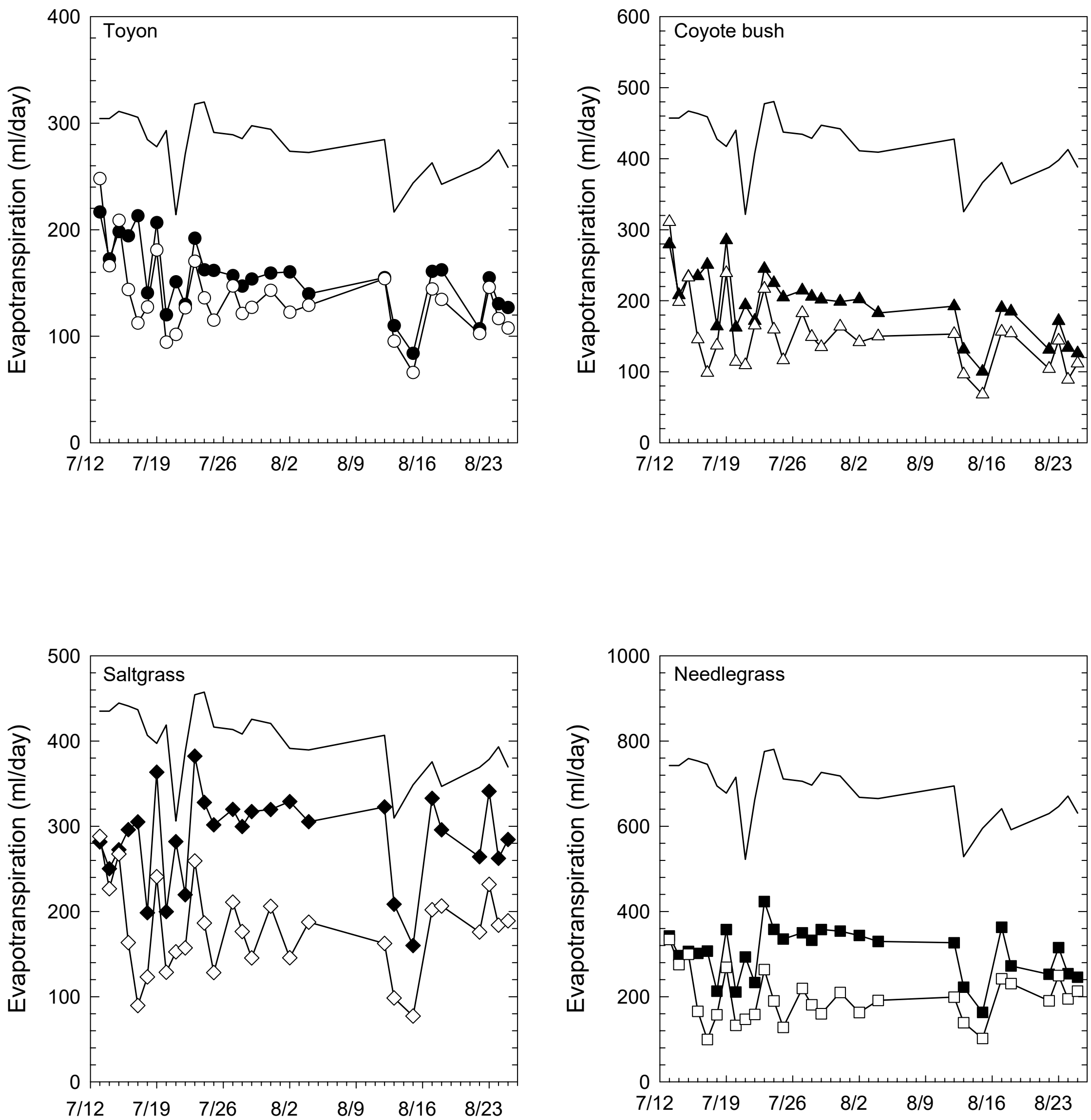

Figure 1. Evapotranspiration of well-watered (solid symbols) and water-stressed (open symbols) plants in one-gallon containers. Solid line represents ET_o calculated for the projected area covered by the canopy of each plant.

Table 1. Evapotranspiration of well-watered and container-grown plants grown in one-gallon containers. Values are based on volume of water evapotranspired over the projected area of the plant canopy. Values in a column followed by the same letter are not significantly different (P=0.05, Tukey's Honestly Significant Difference test). Asterisk denotes a significant different value based on Student's t-test (P=0.05).

Treatment	ET (cm)
Species	
Toyon	0.30 b
Coyote bush	0.22 c
Needlegrass	0.23 c
Saltgrass	0.38 a
Irrigation	
Well-watered	0.33 *
Water-stressed	0.24

Treatment	ET (cm)
Toyon, Well-watered	0.32 b
Toyon, Stressed	0.28 b
Coyote bush, Well-watered	0.25 bcd
Coyote bush, Stressed	0.20 cd
Needlegrass, Well-watered	0.27 bc
Needlegrass, Stressed	0.19 d
Saltgrass, Well-watered	0.47 a
Saltgrass, Stressed	0.28 bc

Table 2. ET coefficients of well-watered and container-grown plants grown in one-gallon containers. Values are based on volume of water evapotranspired over the projected area of the plant canopy and are related to the values of ET_o posted for the Davis CIMIS weather station on the corresponding days. Values in a column followed by the same letter are not significantly different (P=0.05, Tukey's Honestly Significant Difference test). Asterisk denotes a significant different value based on Student's t-test (P=0.05).

Treatment	k
Species	
Toyon	0.52 b
Coyote bush	0.41 c
Needlegrass	0.36 c
Saltgrass	0.58 a
Irrigation	
Well-watered	0.54 *
Water-stressed	0.39

Treatment	k
Toyon, Well-watered	0.56 b
Toyon, Stressed	0.48 bc
Coyote bush, Well-watered	0.46 c
Coyote bush, Stressed	0.36 d
Needlegrass, Well-watered	0.44 c
Needlegrass, Stressed	0.29 d
Saltgrass, Well-watered	0.72 a
Saltgrass, Stressed	0.45 c

between well-watered and stressed plants was greatest for the two grasses and least for Toyon. The total ET volumes per container were greater for the two grasses than for the shrubs, but no difference between these growth forms was evident when ET was corrected for projected area of the canopy (Table 1). The highest average ET in August was 0.47 cm for well-watered Saltgrass. The ET of all other species*irrigation interactions was 0.32 cm or less. All of these values were substantially below ET_o in Davis for those dates. The average ET coefficient (k; ET_{plant}/ ET_o) was less than 0.6 for all species (Table 2). The highest k value for any species*irrigation interaction was 0.72 for well-watered Saltgrass; the lowest was 0.29 for water-stressed Needlegrass.

The relatively rapid response to water stress has been reported for some other species, although some species require a month or more to adjust (Garcia-Navarro et al. 2004). The water use of these species grown in containers is reasonably close to what has been reported in field studies. For example, Coyote bush and Toyon have been shown to grow satisfactorily in inland valleys at irrigation rates of 0.20 ET_o and 0.36 ET_o, respectively (Pittenger et al. 2001; Pittenger and Shaw 2004), and transpiration rates similar to those found here were reported for Saltgrass (El-Haddad and Noaman 2001).

The relationship between ET_o and actual ET was stronger for the shrubs than for the grasses (Figs. 2 and 3). ET_o could account for 36% to 39% of the variation in well-watered shrubs and 25% to 29% of the variation in water-stressed shrubs. With the exception of well-watered Needlegrass, ET_o accounted for only about 10% of the variation in the grasses. This result is not surprising since these plants differed in height and form and were in a mixed planting, whereas the evapotranspiration model was created for relatively large monoculture stands of well-irrigated plants.

Water stress significantly inhibited growth of all four species (Table 3). The sacrifice of growth in favor of water conservation has been well documented for many California grasses and shrubs (Valladares and Pearcy 1997; Holmes and Rice 1996). However, water stress did not significantly affect root dry weight or

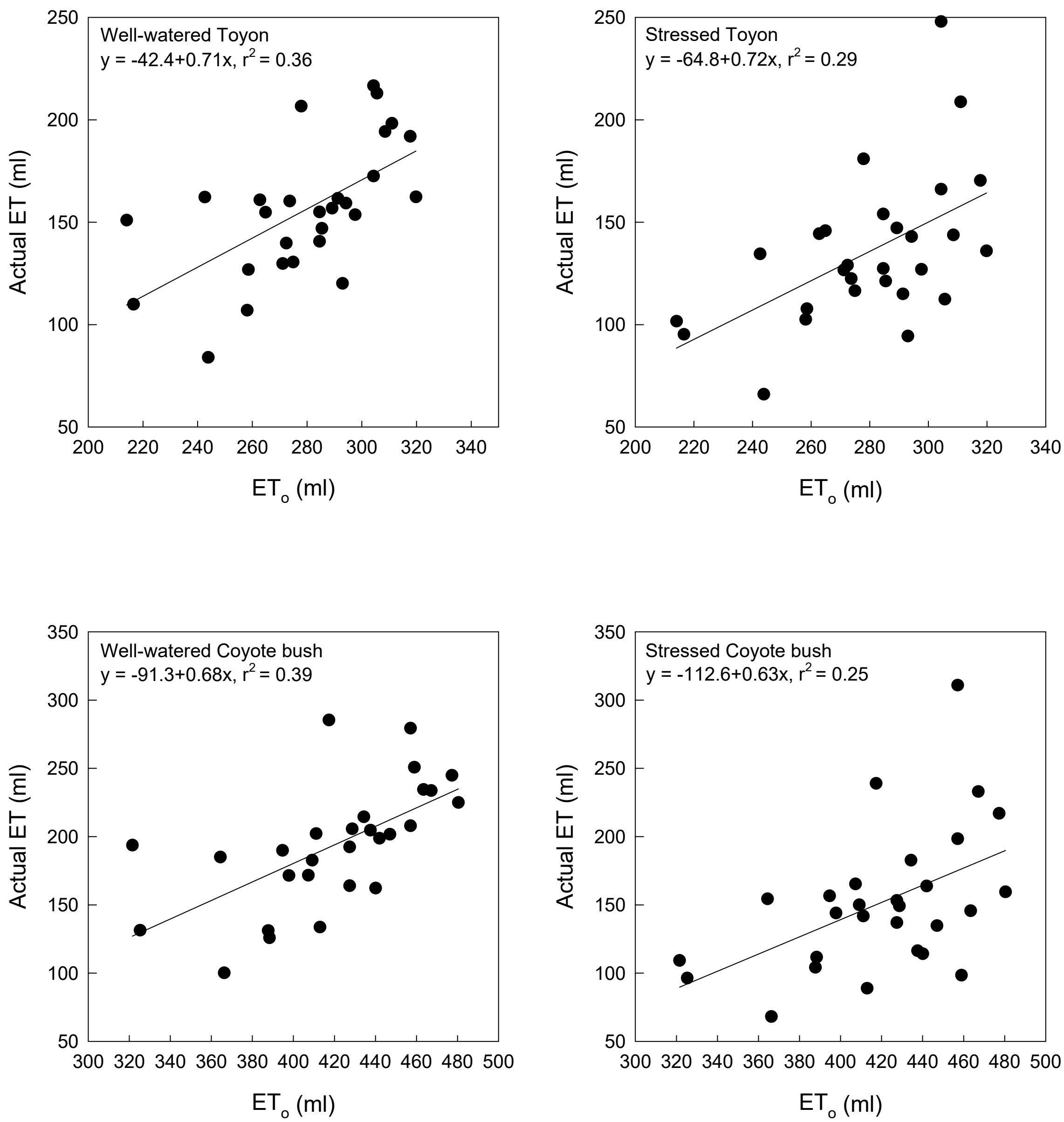

Figure 2. Actual ET as a function of ET_o for well-watered and stressed shrubs grown in one-gallon containers. Volumes of evapotranspiration are based on the projected area of the plant canopies. ET_o values are from the CIMIS weather station in Davis.

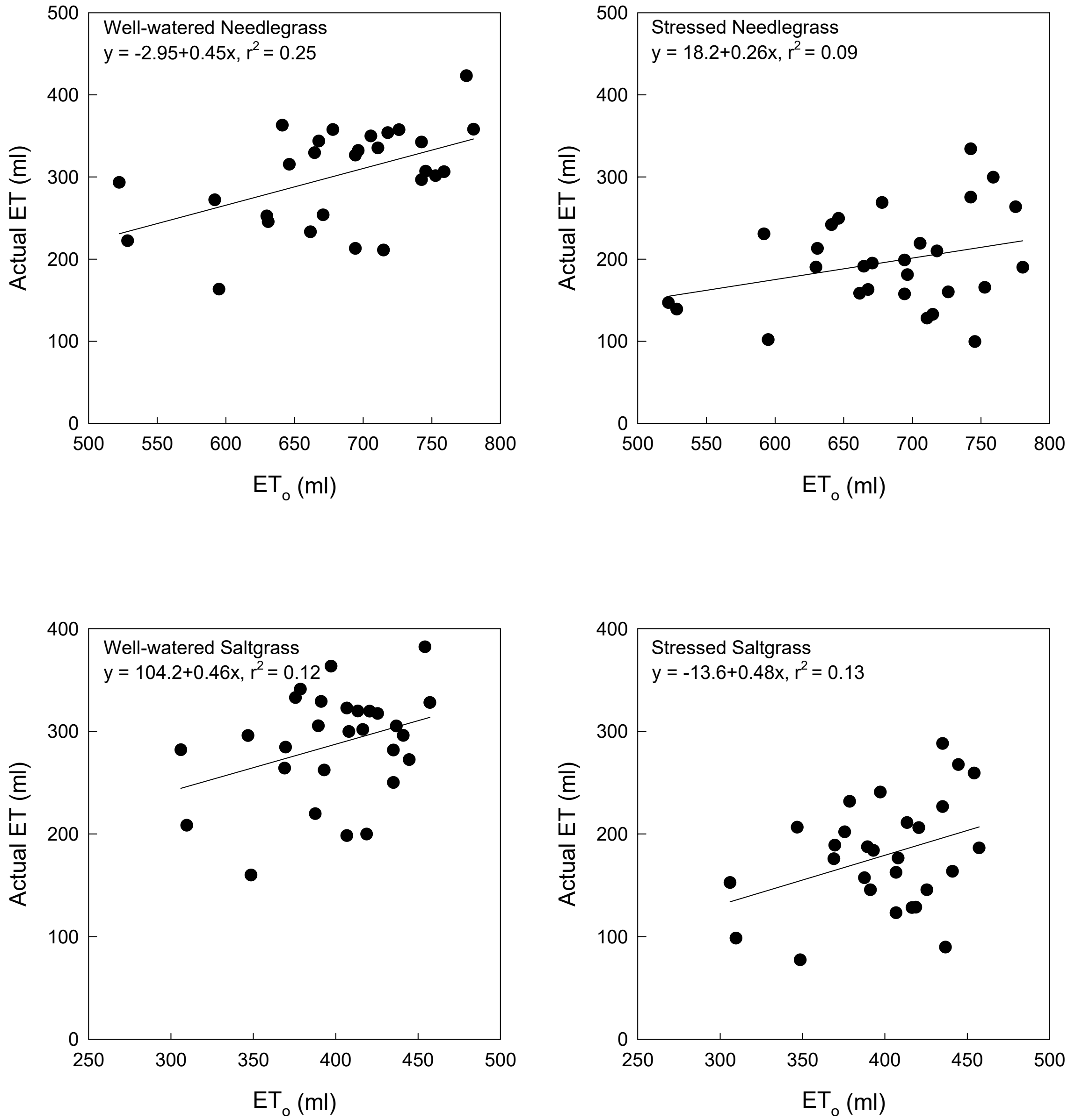

Figure 3. Actual ET as a function of ET_o for well-watered and stressed grasses grown in one-gallon containers. Volumes of evapotranspiration are based on the projected area of the plant canopies. ET_o values are from the CIMIS weather station in Davis.

Table 3. Dry weight, root:shoot ratio, and rhizome number for well-watered and water-stressed plants grown in one-gallon containers. Values in a column followed by the same letter are not significantly different (P=0.05, Tukey's Honestly Significant Difference test).

Treatment	Shoot dry weight (g)	Root dry weight (g)	Root:Shoot ratio	Rhizome number
Toyon, Well-watered	16.4 c	1.75 d	0.11 cd	
Toyon, Stressed	14.3 c	1.10 d	0.08 d	
Coyote bush, Well-watered	13.7 c	2.76 d	0.20 c	
Coyote bush, Stressed	10.8 d	1.83 d	0.17 cd	
Needlegrass, Well-watered	22.1 b	9.87 b	0.45 b	
Needlegrass, Stressed	12.3 cd	5.21 c	0.42 b	
Saltgrass, Well-watered	27.8 a	20.69 a	0.74 a	47.0 a
Saltgrass, Stressed	21.2 b	8.24 b	0.39 b	33.5 b

root:shoot ratio of the shrub species. The greatest effect on shoot dry weight was in Needlegrass, and the greatest effect on root dry weight was in Saltgrass. In the latter species, the effect was probably mainly due to a decrease in the number of rhizomes.

Conclusions

This experiment confirmed our hypothesis that restricted irrigation of plants in containers can be used to decrease transpiration, and that the species under study can acclimate quickly (less than one week) to the relatively rapid onset of water stress. Although water stress reduced growth rates of both grasses and shrubs, the difference in growth did not detract substantially from plant appearance and definitely did not affect survival. These results support the idea that plant response to water stress in containers may be used to predict the response of the same species in field plantings. In addition, application of a short period of water stress at the end of nursery production may harden plants sufficiently to increase their survivorship after transplanting to field sites. One minor concern in this regard is the possibility that the root:shoot ratio may decrease if plants are held too long in production facilities and shoots become too large. Then, if the water stress treatment is prolonged, the low root:shoot ratio may result in transpiration rates that cannot be supported by root uptake of water. In experimental work, this imbalance may generate inaccurate results, while in production scenarios, plants may die from water stress before more roots can be grown.

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Section 4. Laboratory tests of inorganic amendments

Synopsis

This section describes development of an improved method to measure water release from amendments that is more relevant to wild-land plants than conventional methods developed for agronomic systems. A variety of inorganic amendments (IAs) were then tested and the amount of water released with increasing matric tension was measured. A calcined diatomaceous earth product is recommended because it has water release characteristics that fit water use patterns of wild-land plants, including greater water holding capacity at low matric tensions (wet conditions) and greater release of moisture during more negative matric tensions (droughty conditions). This provides more plant-available moisture for wild-land plant utilization during summer drought conditions.

Introduction

Inorganic amendments (IA) such as calcined clays and calcined diatomaceous earth have commonly been added to the root zone of turfgrasses as an alternative to organic soil conditioners. The ability of IAs, in general, to reduce a soil's bulk density while increasing its cation-exchange capacity has been well documented (Bigelow et al. 2004; Li et al. 2000). Conflicting data, however, have been reported about the influence of IAs on plant available water (PAW) (defined as the water held between field capacity (FC, -10 J kg^{-1}) and permanent wilting point (PWP, -1500 J kg^{-1}) (Cassel and Nielsen, 1986; where FC~-10 J kg^{-1} for coarse textured soil)). It is important to note here that the difference between FC and PWP gives only an estimate of PAW since each plant type behaves differently in terms of water use and regulation depending on its phenology (growth stage), physiology (stress resistance) and environmental conditions (soil and atmospheric moisture and temperature conditions). For this reason, the term PAW should be regarded as an estimate for a generalized plant.

Differences in methodologies and materials used to estimate PAW make comparing the results of the following studies difficult. van Bavel et al. (1978)

reported that fritted clay (1-2 mm in size) held 0.31 m^3 m^{-3} PAW. Both Li et al. (2000) and Bigelow et al. (2004), however, found very little available water at pressure potentials less than -10 J kg^{-1} in IA-soil mixtures, which would be a very damp soil condition. Bigelow et al. (2004) noted the unexpectedly low PAW and devised another method of measuring the PWP water content in a pure IA growing media by using a bioassay. The data from the bioassay indicated a lower -1500 J kg^{-1} water content than was determined using the pressure plate method, and resulted in an estimated PAW content of ~0.22 m^3 m^{-3}.

McCoy and Stehouwer (1998) evaluated the water release curves of IA and sand mixtures from saturation to ~ -10000 J kg^{-1} (extremely dry soil conditions). They found a bimodal distribution of water release, where water held between sand and IA particles was released between saturation and ~-3 J kg^{-1}(nearly saturated soil). Water held within the IA particles began to be released at a matric potential of -12.6 J kg^{-1}(very wet soil), but did not begin to release appreciable water until a matric potential of -53 J kg^{-1} (damp soil). The internal pores drained fairly uniformly between -53 and -1000 J kg^{-1} (irrigated agricultural plant water use). This information shows that the majority of internally held water in the IAs that they studied was available within the range of PAW.

The objective of the research reported in this current study was to estimate the PAW of four IAs using a standard method so that comparisons could be made between them.

Methods

We evaluated the PAW of four inorganic amendments (IAs): 1) calcined volcanic ash and diatoms (CAD) (Pozzalon, Lassenite ATS); 2) granular clay (GC)(Soil-Life); 3) calcined diatomaceous earth (CDE) (Axis regular) and 4) zeolite clay (Ecosand). Three replicates of each IA and compost were measured at each matric potential. The pressure plate method was used to determine moisture contents at -0.01, -0.03, and -0.05 MPa. Soil moisture was further desorbed using the pressure plate set to -0.30 -1.0 and -1.5 MPa tensions, but these drier conditions often did not accurately equilibrate. Approximately 5 grams of each IA was then placed above a saturated K_2SO_4 solution in a closed chamber at room temperature. The relative humidity above this solution is fairly constant over a range of temperatures and has a corresponding matric potential of -2.8 MPa. After 24 hrs, the actual matric potential of the IA sample was measured using dew-point potentiometer (WP4-T Decagon Devices). In all cases, the moisture content of the experimentally equilibrated sample was determined by comparison of the equilibrated weight and its oven dried weight. Gravimetric water content of these samples was then converted to volumetric water content by multiplying the gravimetric water content by the IA bulk density.

The moisture content at -1.5 MPa was determined by assuming linear relationship between the matric potential and IA moisture content at moisture levels near the target potential of -1.5 MPa. In general, the portion of the moisture release curve below -1.0 MPa was quite linear (Figure 1). The difference between water contents at -0.01 MPa and -1.5 MPa was determined to represent PAW.

Results and Discussion

Water release data from Figure 1 shows that inorganic amendments hold the most water at saturation (-0 MPa) and have progressively less water content as more matric tension is applied (reading rightward on the X axis of the graph to -2.5 MPa). At saturation, IAs have between 21 and 46 % moisture content but at their driest, they have between 8 and 18 % moisture. These plot lines are prorated for moisture content at -1.5 MPa, giving values between 11.8 and 18.5 % (Table 1.).

The shape of the water loss trace, and the steepness of the slope, indicates how fast water is being lost from the IA with increasing tension. The calcined diatomacious earth (CDE) holds the most moisture from saturation to field capacity (FC) and then releases moisture through the tensions at which plants wilt, from -1.5 to -2.5 MPa. At -2.5 MPa, this material would still retain less than 5 % moisture, having released the rest for plant uptake. In contrast, the Zeolite holds about 22% moisture at saturation and declines to about 17 % at 1.0

MPa and only about 16 % at -1.5 MPa. Under much drier conditions at -2.5 MPa only an additional 1 or 2 % is released.

From the difference between saturated and desiccated states (standardized for -1.5 MPa tension levels), the CDE material releases about 34 % moisture for plant growth (PAW) while the Zeolite releases about 6 %. The GC and CAD materials are intermediate. The CDE material has an additional beneficial characteristic in that it releases moisture during stressful soil moisture conditions for the plant (-1.5 to -2.5 MPa), which provides ecologically valuable moisture during droughty conditions. The amount of moisture released over a wide range of matric tensions is expected to be due to a range of larger and smaller pore sizes within the calcined material, although this was not tested. Since it is a physical, not a chemical, process, no decrease in function is expected with multiple wet/dry cycles, as is the case for organic polymer materials.

Using a combination of the pressure plate method and a constant humidity chamber, the PAW contents (v/v) of the CDE and CAD were comparable to those reported by van Bavel et al. (1978). Results indicate that not all IAs would increase PAW in soils. Specifically, this would be the case in soils that have an ambient PAW content greater than the IA. The CDE IA provided the greatest amount of PAW (Table 1, ~34 % v/v) and is recommended to be used as a soil amendment to increase soil water availability. Normal application rate is 10-20 % by volume.

Table 1. Moisture release characteristics of four inorganic amendments

	Bulk Density g/cm3	-0.01 MPa* v/v	-1.5 MPa* v/v	PAW* v/v
calcined ash diatoms (< 1 mm) (CAD)	0.74	0.410 b	0.185 a	0.224 b
granular clay (GC)	0.65	0.311 c	0.133 c	0.178 c
calcined diatomaceous earth (CDE)	0.39	0.456 a	0.118 d	0.338 a
zeolite clay (Zeolite)	0.94	0.216 d	0.157 b	0.059 d

* PAW: Plant Available Water. MPa: MegaPascal matric tension (= 10 bar)
Values within each row followed by the same letters differ not significantly ($p < 0.05$)

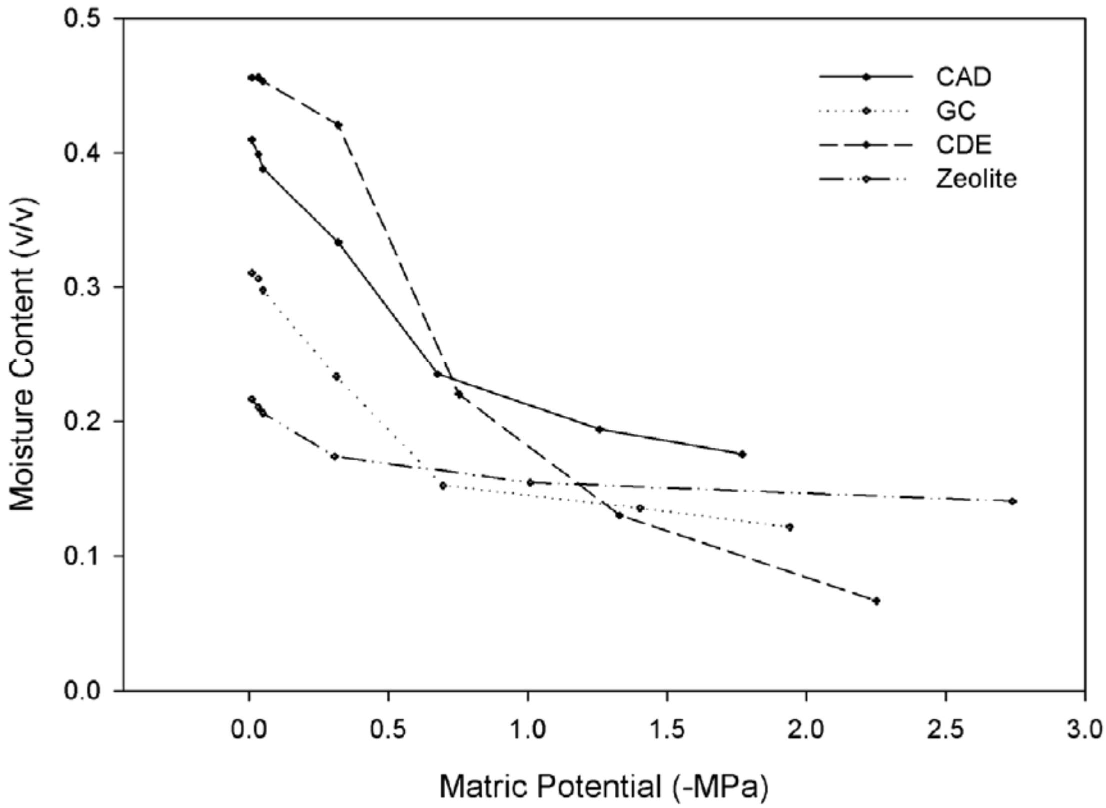

Figure 1. Water release curves for four inorganic amendments

Conclusions

The combination of technical methods developed here provides more accurate evaluation of moisture release from these inorganic amendments (IA) than conventional soil moisture testing methods. Water release patterns of different IAs or mixtures can easily be measured in the lab so that field use and management decisions can be made with no further testing, if the product characteristics do not change. The recommended material of those tested here is calcined diatomaceous earth (CDE). Its use is recommended for droughty substrates that need additional PAW. Examples of these substrates are materials with sandy textures through loam-textures. This IA material should be used in more arid conditions or rocky sites where amendment with IA is cheaper than developing additional moisture availability through deeper decompaction and deeper rooting. For example, very sandy substrates with low water holding capacity may require very deep tillage and large rooting volumes, which may be reduced if amended with an IA. Another potential use would be slopes or rocky areas where hard rock or geotechnical issues limit greater depth of decompaction or rooting. In most typical large field site applications, however, decompaction of substrates to increase rooting depth will probably provide additional moisture availability less expensively than incorporation of an inorganic amendment simply because increasing rooting volume through fracturing is probably cheaper than purchase, application and incorporation of 20 % or more of the substrate volume with an amendment.

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Section 5. Demonstration plots in Contra Costa County, State Route 4 in Central California

Synopsis

A field trial was constructed within the highway right-of-way along SR 4 in Contra Costa County to measure shrub growth response to selected soil treatments that increase plant available water (PAW), in comparison to irrigated plots. Toyon, coyote bush and purple needlegrass were used as trial plant species. Treatments compared irrigation, decompaction alone, compost amendment, water retaining hydrogels, mats and mulches, all in contrast to control plots of untreated substrate. Shrub growth with soil decompaction and compost amendment was equal to or greater than growth on watered plots or with inorganic amendments.

Introduction

The water-use data collected from the greenhouse experiment and from published values, along with data from the inorganic amendment plant available water experiment, was used to design demonstration plot treatments having adequate plant available water in summer field conditions. Initially, water-use dynamics were estimated using static pool methods, meaning that total seasonal water use by the plant was contrasted with seasonal water supply in the soil, assuming a fully wetted profile. As information was gathered, the model was refined to address shorter time steps than a whole season, first using monthly averages and later using daily averages. This eventually allowed a more realistic understanding of plant water-use behaviors and more appropriate soil treatments for replacement of irrigation. For field plot design, static pool estimates were used to design and construct plots and plant growth was monitored to document how they grew into the soil water supply available to them.

Materials and Methods

The unamended fill slope at Contra Costa SR 4 (CC 4 post mile 7.5) was estimated to contain 60 % coarse fragments (rocks) and only 40 % fine soil (Table 1). In the unamended fill slope, there was estimated to be 65 mm of cumulative moisture in the top meter but it was not 'plant available' because the surface soils are very rocky and were compacted during slope construction, restricting root growth. The field trial plan called for excavation and disruption of compaction, opening up the substrate to a rooting depth of 1 m. Amendments were restricted to the top 500 mm depth to better represent what could be achieved in a production scale installation (Table 2).

Table 4. Influence of CDE (added at 20 % by volume) on soil water holding properties.

Treatment	-0.01 MPa (v/v)	-1.5 MPa (v/v)	PAW (v/v)	Crs frag cont %	PAW adj for Crs frags (v/v)
CDE	32.8	12.5	20.3	50	10.2
HW 4 soil	28.3	12	16.4	60	6.5

Table 2. List of soil treatments at the Contra Costa SR 4 site.

1) No Till w/o mulch (minus-minus)
2) No Till with mulch (minus)
3) No Till + water retaining gel with mulch
4) No Till + irrigate with mulch
5) Till with mulch
6) Till + irrigate with mulch
7) Till + 20 % compost with mulch
8) Till + 20 % calcined diatomaceous earth (CDE) with mulch

The soil in each plot was modified by mechanical decompaction (excavation and replacement) and/or soil amendment such that the plot contained the amount of moisture needed to support toyon growth through the summer. When toyon plants were water stressed in the preliminary greenhouse study they used 0.63 mm of water per day. Based on a 100 to 130 day dry period this would require 63 to 82 mm of available water in the soil profile. The other plant types were estimated to need more water but by planting them in these plots we could check to see if they could survive with very minimal water resources.

The treatments increased water availability in the top 500 mm depth from having a PAW of 32.5 mm (ambient soil) to 36 mm (20% compost addition (v/v), PAW ~10 %, data not shown), or 51 mm (with 20 % calcined diatomaceous earth (CDE) (v/v)). The total profile moisture content of the top meter (after amendment to a half meter) would be 68.5 mm (in compost plots) to 83.5 mm (CDE plots), which is in the range estimated for water use by stressed toyon plants.

Soil tillage was done on appropriate plots (Till or Till plus amendment) with a wheel mounted backhoe. Tillage was done to 1 m to disrupt compaction layers, and then refilled to 0.5 m depth. Then, the soil for the top 0.5 m in the Compost and CDE plots was refilled and mixed with the amendment during replacement.

All treatments were replicated 4 times in a completely randomized design across the bottom of the slope (8 treatments x 4 replications = 32 plots). Non-woven weed mat was placed over plots (except in the No Till w/o mulch treatment) and 1 - 2 inches of wood chips were used as a mulch. The mulch was used as a technique to conserve available soil water so that it could be utilized by the plant and not lost to evaporation.

Soil treatments were designed such that the No Till and Till treatments each had ~70 mm of available water in their top 1 m of soil. The Compost treatment had ~73 mm of water available of water in the top 1 m of soil. The CDE treatment had ~85 mm of water available in the top 1 m of soil. The water-retaining gel treatments were calibrated to increase the amount of available water in the ambient soil to 85 mm. This required 8 L of water retaining gel (Dri-water) over the growing season. The gel was applied July 3, 2006 (2 L per plant), August 1, 2006 (2 L), September 1, 2006 (2 L), October 2, 2006 (2 L). Irrigation treatments required watering at monthly intervals beginning in June. The amount of water applied brought the top 20 cm of soil to field capacity.

Assuming they were at -1.0 MPa then ~3 L of water would need to be added to increase the <2 mm fraction back to field capacity.

Four plant types were planted at the site: coyote bush (*Baccharis pilularis*), toyon (*Heteromeles arbutifolia*), blue oak (*Quercus kelloggii*) and purple needlegrass (*Nassella pulchra*). The shrubs were planted from container stock (2.5 x 10 inch pot) and the grass was planted from plugs. Both were from appropriately regional accessions. Shrub plots were 2 x 3 m in size and coyote bush and toyon were planted in 1.5x1.5m sections at the lower left and lower right corners. The top 0.5 x 3 section was planted with two individual oaks as unmonitored demonstration plantings. Coyote bush and toyon were planted 0.75 m on center (4 per plot) in the left and right corners. Grass plots were established as 1 x 1 m plantings and purple needlegrass plugs were planted in a 4 x 5 plant grid at 0.2 m on center. All plants were fertilized at the time of planting with slow-release resin coated fertilizer prills (9-6-12 NPK content) to assure nutrient sufficiency.

Figure 1. Demonstration plots at CC SR 4 after construction in February 2006.

Figure 2. Water retaining gel installation at Contra Costa SR 4

Monitoring

Plant data was collected from the plots in October 2006 after the first season's growth in winter and spring of 2006. Canopy volume (height x widest canopy axis x perpendicular axis) was used as the method of assessing shrub plant vigor (Figures 5, 6 and 7). Canopy volume measurement is a non-destructive method and will allow comparisons to be made on the same plots for multiple seasons.

Statistics

Significance of treatment results was tested using a one way ANOVA and treatment mean values were separated for the toyon and coyote bush canopy volumes using an Least Significant Difference test at $p = 0.1$. This level of confidence was used because of the extreme variability of field conditions, as will be discussed below. Oak tree height was measured and compared between treatments. Means could not be separated because the probability of the null hypothesis being correct in the one way ANOVA was greater than $p = 0.1$. Grass biomass was measured on each plot. Plants were clipped ~1 cm above the soil surface. Only the interior six plants of the planting grid were sampled in order to avoid edge effects.

Figure 3. Monthly irrigation of plants during the first summer after planting.

Results and Discussion

First year's plant growth (Fall 2006)

The first season growth of toyon was greatest for tilled and irrigated plants (Figure 4). This treatment provided rooting depth as well as surface watering and represents the current practice of irrigated roadside vegetation. Tilled plus compost growth was smaller, but did not statistically differ. Plant volume of the tilled treatment was similar to the compost, CDE and non-tilled irrigated treatments. Although all plants were fertilized at the time of planting with slow release fertilizer, the compost treatment showed significant additional growth, indicating other, non-nutrient effects for this amendment.

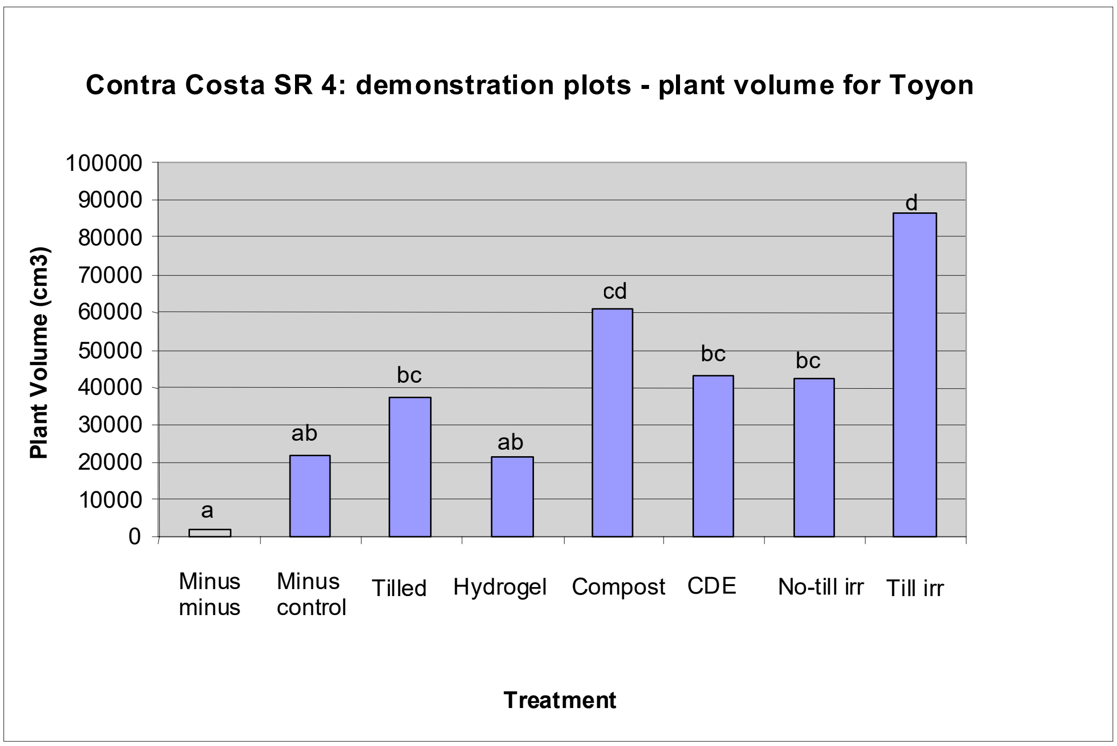


Figure 4. Plant canopy growth for toyon after first season in fall 2006. Columns topped with the same letter do not statistically differ (p = 0.05).

Treatment key: Minus minus: non tilled and non irrigated and has no weed-mat or mulch; Minus control: non tilled and non irrigated but has weed-mat and mulch; Hydrogel: non tilled with gel amendment; No-till irr: non tilled and irrigated monthly; Tilled: excavate and replace to 1 m only; Till irr: tilled to 0.5 m and irrigated monthly; CDE: Tilled with calcined diatomaceous earth mixed; Compost: tilled with compost mixed.

The no-till / no-mulch (minus-minus) treatment which had no weed-mat or mulch demonstrated the influence of competition on plant growth. Annual grasses had nearly covered the toyon bushes in this treatment. The minus control (non tilled but with a weed-mat and mulch) was not significantly different from the tilled, water gel, CDE and non tilled irrigated treatment. For toyon this indicates that, if rooting is minimally adequate, no soil tillage, amendments or supplemental irrigation are needed as long as the influence of competition from other plants is removed (as by use of a weed-mat and mulch). The slow, stress-tolerant growth makes it less competitive against weedy growth or faster growing shrubs. These first year data indicate that amending the soil with compost to increase the soil water resources provides plant growth approaching that of current irrigation practices.

Coyote bush flourished at the CC SR 4 site the first year. Plant volumes for coyote bush were an order of magnitude greater than toyon (Figure 5). In six months the diameter of the shrubs grew from <1 cm at planting to 3.7 cm (Figure 6). The plants in the minus minus (no mat or mulch) treatment were overwhelmed by competition from annual grasses, similar to toyon. The minus control treatment (mat and mulch but no tillage) had significantly greater plant volume than the minus minus treatment. Again this shows the importance of removing competition for the establishment of roadside vegetation. As with toyon, the tilled and irrigated treatment showed the greatest response. Irrigation alone did not prove to be an effective way to maximize plant growth. The treatments that both included tillage and some method to increase soil water resources (compost and CDE treatments) most closely matched the plant growth of the tilled and irrigated treatment. Amendment with hydrous gels gave moderate growth improvement only for grass plugs in the first year. Growth of baccharis or toyon shrubs with gel treatment after the first summer season was less than for compost or till / irrigate treatments (Figure 4, 5) as measured by shrub canopy volume.

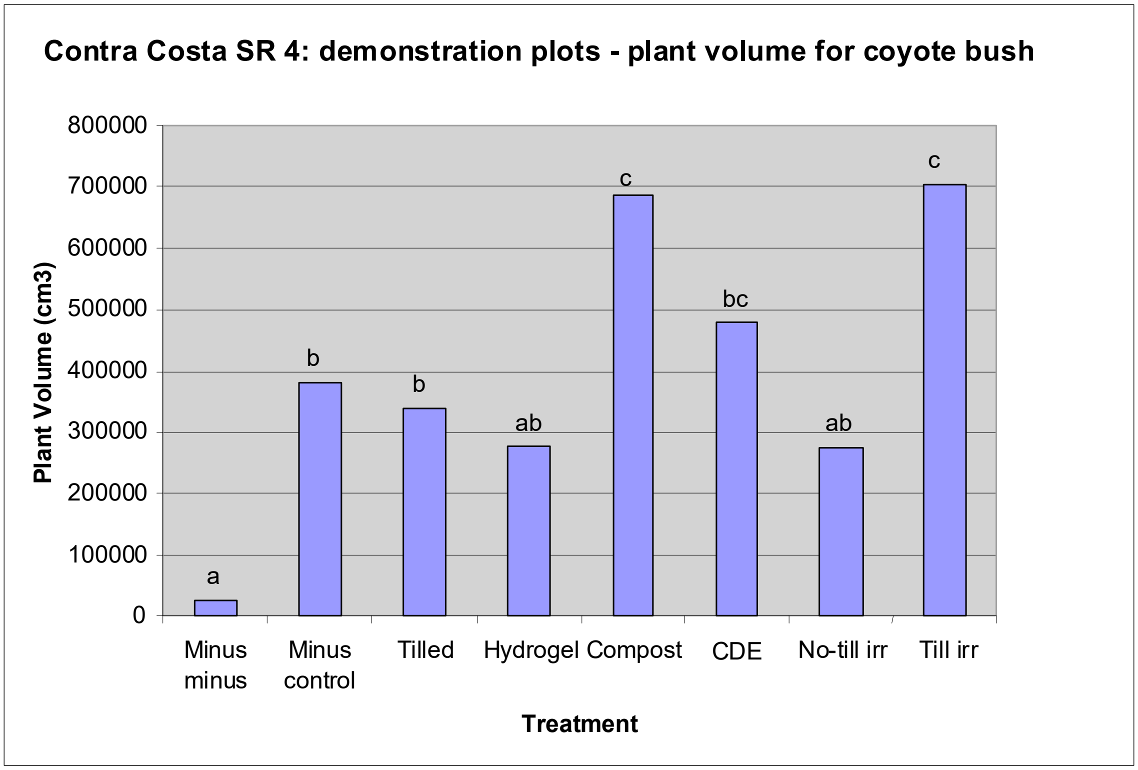


Figure 5. Plant canopy growth for coyote bush after first season in fall 2006.

Figure 6. Coyote bush basal diameter (1.5 inches) after six months of growth.

Biomass clippings from the perennial grass plots showed that irrigation alone was not the only limiting factor. The tilled-irrigated treatment did not have greater biomass than the tilled only treatment (Figure 7). Nutrients or compost mediated root growth seemed to be limiting factors since the compost treatment showed the greatest plant biomass. Increasing rooting (tillage) and minimizing competition (weed-mat and mulch) would allow perennial grasses to become established at this location without the need to irrigate. Hydrogel amendment showed plant growth increases in the first year only for grasses, not shrubs.

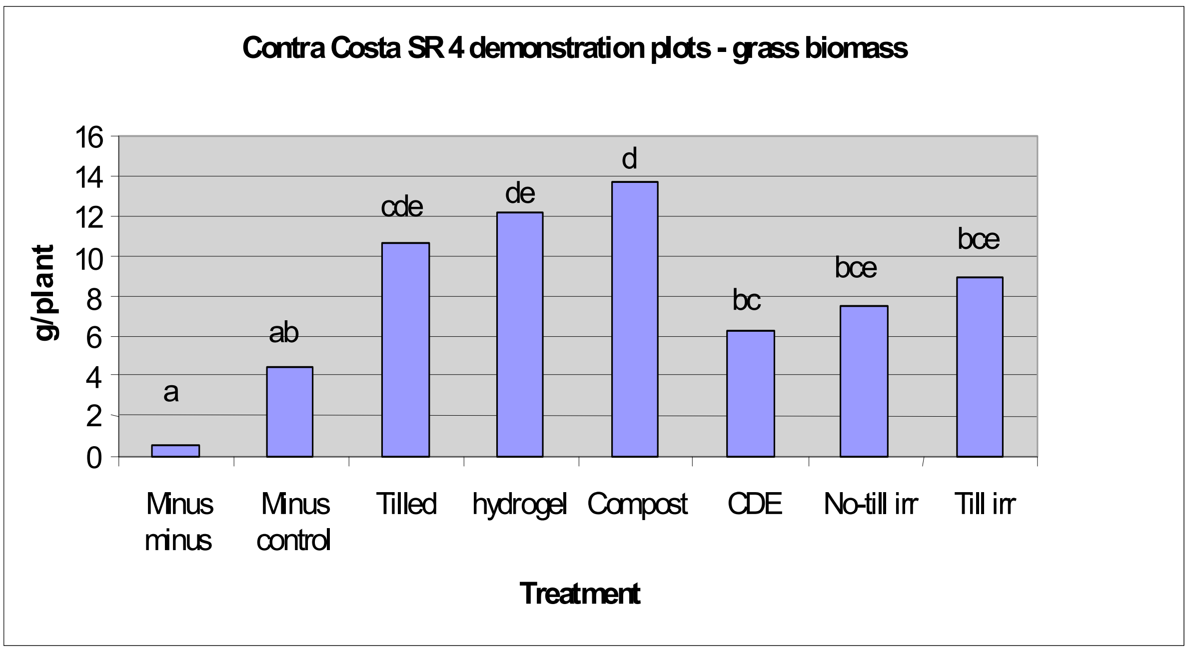


Figure 7. Plant canopy growth for purple needlegrass after first season in fall 2006.

Although survival and growth without irrigation for both shrubs in all treatments except the minus minus treatment was very good, it must be noted that 2006 was a very wet year. Also the experiment was performed at the base of a fill slope instead of a cut slope with harsher site conditions (Figure 8). Water resources are often more limiting on cut slopes. In fact, on the fill slope we saw areas of seepage that stayed wet long after it stopped raining. The fill slope had been a monoculture of annual grasses and mustards. Perhaps the reason for the absence of shrubs and trees was the intense competition from the annuals, as seen in out minus minus treatment. In any event we did see greater growth in treatments that had increased soil water resources.

Figure 8. Photo of CC SR 4 site in fall 2006.

Data for the oak tree height is not presented. A one-way ANOVA showed that there was no difference between treatments. The time scale of one growing season was not very long and plants were expected to be growing root rather than shoot biomass. Perhaps longer term data would show treatment differences. Oaks in all treatments survived including in the minus minus treatment, however growth was minimal and average plant height was ~9 cm. This was roughly the same height as the containers were at planting.

Biomass data for the second year were similar to the third year, but less distinct. For simplicity, only third year statistical data are shown.

Third year's plant growth (Fall 2008)

By the end of the third growing season, large growth differences occurred between treatments (Figure 9, 10). The larger coyote bush plants were 1.5 m (5 feet) tall while surviving plants on the least effective treatments for this location were 0.5 m (18 inches) tall. Toyon plants tended to grow more upright and

Figure 9. Coyote bush and toyon shrubs in late summer 2008. Larger shrubs are 1.5 m (5 feet) high. View is to the west in the upper photo and to the east in the lower photo.

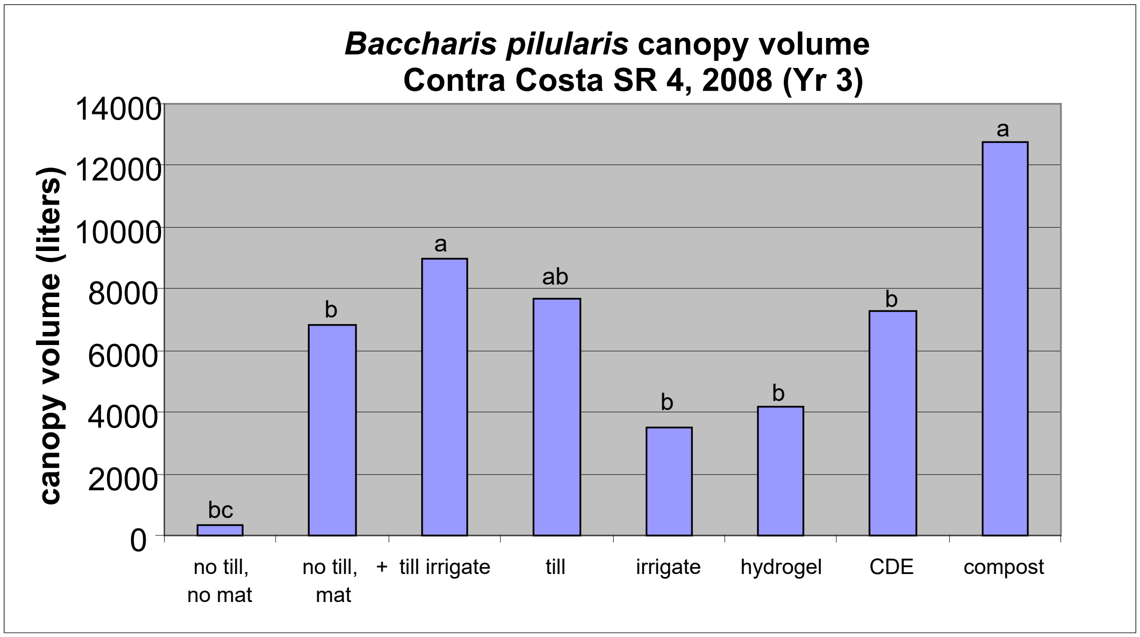


Figure 10. Plant canopy volumes after three seasons for coyote bush in fall 2008.

Treatment key: Minus minus: non tilled and non irrigated and has no weed-mat or mulch; Minus control: non tilled and non irrigated but has weed-mat and mulch; Hydrogel: non tilled with gel amendment; No-till irr: non tilled and irrigated monthly; Tilled: excavate and replace to 1 m only; Till irr: tilled to 0.5 m and irrigated monthly; CDE: Tilled with calcined diatomaceous earth mixed; Compost: tilled with compost mixed.

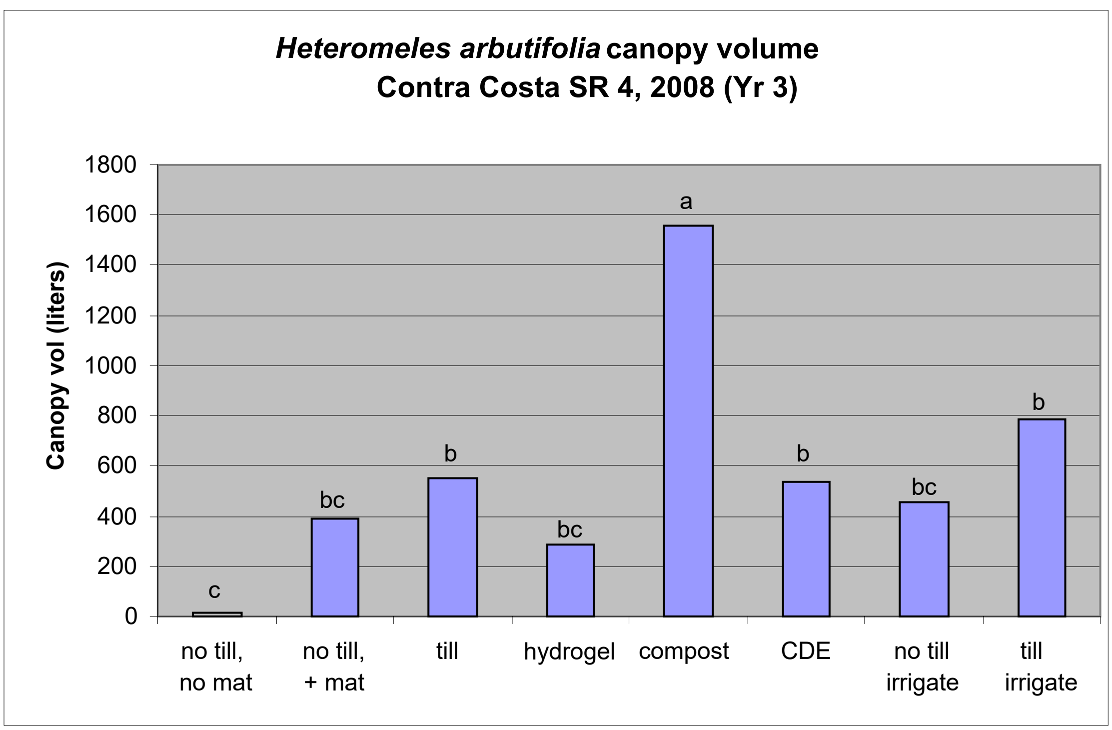


Figure 11. Plant canopy volumes after three seasons for Toyon in fall 2008.

narrow and were generally equal to or half as tall in as the coyote bush in each treatment, but they had only about one tenth of the canopy volume.

On harsher treatments, survival and plant height was about even between toyon and coyote bush. On more favorable treatments, however, coyote bush often crowded and over grew toyon. Although the till plus compost treatment was clearly the most favorable for toyon, experimental variability in the coyote bush plots created non-significant differences between compost till, till irrigate and till only treatment. Partly, this result can be understood because the plots were located at the base of a fill slope that allowed subsurface moisture through the early part of the year. Tillage allowed the plants to acquire this ambient moisture. Locations without this enhanced moisture availability may show stronger response to tillage treatments, if moisture can be accumulated through the winter, or to supplemental water amendments if no other source of moisture is available. Site conditions influence treatment response, but in general, capture and storage of winter rains gave plant growth equal to or better than irrigation. No long lasting effects of hydrous gels or inorganic amendments were noted after the third summer season for either shrub species. Compost and sometimes tillage were the treatments showing the greatest plant growth response.

Many individual oak plants showed elongation of terminal leaders, but response was variable. Grasses also responded well to treatments, but they were so intergrown with annuals that canopy volume or clipped biomass measurements were not possible to measure.

Figure 12. Compost till treatment with toyon (right) and coyote bush (left).

Figure 13. A non tilled, non mulched, no mat (minus minus) treatment with toyon (right) and coyote bush (left).

Figure 14. Coyote bush (*Baccharis pilularis*) shrubs approximately 2 m (6 feet) tall in winter, 2009.

Conclusions and recommendations

Our results show that plant growth on substrates that have been treated to increase soil water availability can approach the level of growth attained on watered treatments. Shrub growth on compost and tillage or inorganic amendment treatments (in the case of coyote bush) was equal to tilled and irrigated treatments for shrubs. In the first year, the faster growing, herbaceous grasses responded with the greatest growth in treatments with compost and tillage, tillage alone or with a water-retaining gel. But, by the third year, no gels or inorganic soil amendment treatments increased plant growth as much as compost, or, for some species, tillage for increased root volume. With proper soil treatment, irrigation was not needed to establish shrubs in this wild-land situation.

The variable amount of plant growth response on these demonstration plots shows that these wild-land plants adjust growth to fill their available resources. While it is possible to grow toyon on very shallow soils, it may end up resembling a small bonsai plant rather than a larger, vigorous shrub that provides both structural and surface protection to the roadside. For routine production treatment of field sites, a more expedient tillage method such as a ripper shank should be used rather than excavation of individual plots, which was used here only for experimental control.

Many roadside vegetation plantings have specific targets for plant cover for individual species in addition to requirements for numerical survival, vigorous plant growth or increased plant cover. In order to meet this goal it is necessary use site specific data that relates soil water resources with plant needs. Evapo-transpiration models have been used for years in agricultural systems to determine the water-use needs of specific crops at various locations, in order to attain large biomass production. This study demonstrates that literature values and evapo-transpiration model parameters specific for wild-land plants and field weather data can be used to design treatments that allow shrub establishment without irrigation at other sites around California, under different soil and climatic conditions than those observed at Contra Costa County.

Section 6. Additional Statewide Demonstration Plots

Synopsis

This section applies the results from the previous Contra Costa SR 4 field trial plots, from modeling data and methods and from lab analysis of water holding capacities of substrates and treatments. These findings are applied to evaluation of additional, unevaluated field sites where mitigation plantings may occur. Field trials demonstrated that soil treatments can regenerate plantings without irrigation. The wide variation in site conditions and plant response around the state emphasizes that site evaluation methods need to be refined to improve plant growth and to improve the efficiency of soil treatment.

Introduction

A series of plots were installed at three other locations statewide in addition to Contra Costa County that were designed to test whether soil treatments to increase plant-available soil moisture would result in an increase plant survival and growth in the absence of irrigation. Climatic inputs of rainfall and evapotranspiration, substrate texture and water holding capacity, and plant water use characteristics were used to estimate appropriate substrate treatments for each of the additional sites in Yuba, Mono and San Diego Counties.

Materials and Methods

Two of the three additional statewide demonstration plots were constructed in an excavated-basin format (excavate with backhoe, mix and replace) in order to carefully modify and test the ability of soil treatments to increase soil rooting and moisture availability. These plot formats are not recommended as routine construction methods but, rather, are used to better control changes in soil conditions. In all cases, the plot size or plant density was adjusted to provide an estimated adequate amount of plant available moisture. Plant response to these treatments can then be attained using a variety of more rapid, but less controlled, soil treatments for routine field site construction.

The two locations that utilized a tilled-basin format were Yuba County (YUB SR 70 post mile 1.5) and San Diego County (SD I-5, 1/4 mile north of the Solana Beach exit, west side). At both locations, treatments were constructed in 3 x 3 m (9.8 x 9.8 feet) plots tilled to 800 - 850 mm (31.5 - 33.5 in). Plants were installed in 5 x 5 grids of 25 plants on each plot, using container grown plants pruned to 75 to 100 mm (3 - 4 inch) tall from 2.5 x 10 inch pots of coyote bush (*Baccharis pilularis*) plants propagated commercially from regionally collected biological material. Only the center 9 plants were used to evaluate differences in plant growth. Plants were installed at a density predicted to allow sufficient moisture uptake, which was 850 mm (33.5") on center at Yuba (18 % cover) and 800 mm (31.5") on center at San Diego (20 % cover).

At the Yuba County location, two deep tilled plot treatments were built. One was installed with a plastic liner to limit deeper root growth and the other treatment had unlined plots. At San Diego, all plots were lined because the substrate was fractured and would allow varying degrees of water drainage.

At the Yuba County location, all plots were amended with 10 % (v/v) fine compost to provide nutrients and drainage. At San Diego, one set of plots was tilled only and one set had 10 % (v/v) compost mixed to depth.

The practical effect of using weed mat and mulch for container plantings was evaluated by creating duplicate plots that were either planted directly into the untreated substrate or were covered with a synthetic spun weed mat and covered with two inches of clean wood chips for mulch protection.

The remaining statewide demonstration plot was constructed at Lee Vining in Mono County (MON US 395 post mile 46.5). A similar set of plots to Yuba SR 70 was created, but with slightly larger excavated soil volumes (4 x 4 m; 13 x 13 feet). The site was planted with Basin big sage (*Artemisia tridentata*), which is a more regionally appropriate shrub than coyote bush. Sagebrush seedlings 150 mm (6 inch root; trimmed to 75 mm (3 inches) shoot before planting) were collected from areas with dense seedling recruitment within the median near Lee Vining and planted at 950 mm (37.4 inches) on center to balance available moisture and plant growth. The first year survival of these plants, however, was very low due to one or more of several potential negative effects including 1) scarce winter moisture, 2) invasion by Russian thistle, 3) abundant rodent activity, or 4) unintended compost effects. This last possibility may be related to a slight increase of nutrient salts content from yardwaste compost that may be detrimental to plant establishment on these very droughty desert sites, or to a combination of reduced dry soil water content or rapid weed growth and water use. Plants that did survive (1 - 3 per plot, typically in plot edge positions) grew rapidly and surpassed three year old plants in size by the end of the first growing season.

Long term (3 year) monitoring data was collected from a pilot scale experiment that was installed during the first year of the study. These plots involved low intensity treatments including installation of locally collected seedlings (150 mm roots, 75 mm tops) installed in 1) non-treated roadway median substrate; 2) shallow (150 mm; 6 in) tillage (200 mm; 4 inch auger hole) plus 10 % (v/v) fine compost addition; 3) deep (600 to 750 mm; 24 to 30 inches) tillage by auger plus 10 % fine compost; or addition of 20 % calcined diatomaceous earth (CDE) to shallow holes to compare growth to unamended shallow versus deep tilled holes. All treatments were replicated on a grid pattern with 2 m (6 foot) plant spacing for non-interference between plantings. All treatments were planted with Basin big sage (*Artemisia tridentata*) and squirreltail (*Elymus elymoides*). Only zero and deep treatments were planted to antelope bitterbrush (*Purshia tridentata*). These are the results presented in this study.

Canopy volume was measured using a non-destructive method involving the product of plant height times plant canopy width in the longest dimension times the canopy width in a perpendicular direction to the longest dimension.

Results are evaluated by analysis of variance, with mean separation using Least Significant Difference methods using p = 0.10.

Modeling

Modeling parameters are listed, as in the Yuba site example in Figure 1. This table shows evaporation and precipitation levels tabulated in monthly intervals and compared with various plant water use factors, including Kc (crop coefficient), ground cover (%), and soil moisture depletion. The potential evapotranspiration of a plant species is down-regulated by the Ks (stress

Weather or ET_o Data Entry

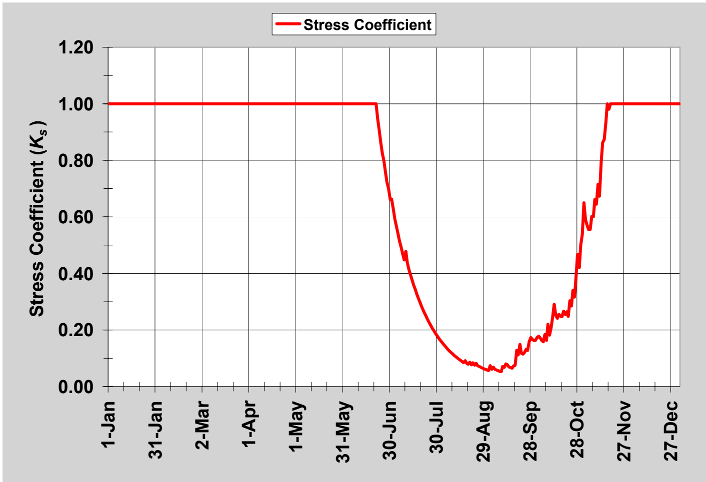
Year:	2006	Latitude:	39.2
Station Name:	Yuba	Elevation (m):	940.0
Available WHC:	0.161 m H2O per m Soil	Slope:	0 (0° = horizontal; 90° = vertical)
Smaller of Root or Soil Depth:	0.85 m	Orientation:	0 (+ 90° east; 0° south; -90° west)

													Default = 1.00	70		50	1.00
	R_s	T_x	T_n	U_2	T_d	Pcp	NRD	Loc. ET_o	Reg. ET_o	Input ET_o	PM ET_o	HS ET_o	$0<K_v$ Veg. Factor	0-100 Gnd. Cov.	$0<K_d<1$ Dens. factor	$0<K_s<100$ Allow. Depl.	$0<K_m$ Clim. factor
Mon	MJ $m^{-2}d^{-1}$	°C	°C	m $^{-1}$	°C	mm	#	mm	mm	mm	mm	mm	K_v	%	K_d	%	K_m
1	6.5	12.7	3.6	2.6	5.4	102.6	8.6	1.0	0.8	0.83368	1.0	1.1	0.96	16	0.35	64	1.20
2	10.4	16.0	5.0	2.7	6.6	107.3	6.5	1.7	1.5	1.51492	1.7	1.8	0.96	16	0.35	64	1.12
3	15.9	19.0	6.0	2.7	7.2	69.6	5.8	2.8	2.6	2.64699	2.8	2.9	0.96	16	0.35	64	1.04
4	21.5	22.8	7.8	3.0	6.9	17.8	1.7	4.4	3.9	3.91792	4.4	4.2	0.96	16	0.35	64	1.13
5	25.5	26.3	10.4	3.0	9.2	19.0	1.5	5.6	5.1	5.14797	5.6	5.4	0.96	16	0.35	64	1.08
6	28.8	30.1	12.7	3.0	10.8	6.0	0.6	6.8	6.4	6.41936	6.8	6.4	0.96	16	0.35	64	1.06
7	29.0	32.9	13.7	2.7	12.7	3.3	0.3	7.1	6.8	6.84605	7.1	6.9	0.96	16	0.35	64	1.04
8	26.0	32.5	13.2	2.5	11.5	2.3	0.1	6.5	6.0	6.02156	6.5	6.1	0.96	16	0.35	64	1.08
9	20.9	30.8	12.1	2.4	10.2	7.4	0.7	5.3	4.8	4.76517	5.3	4.8	0.96	16	0.35	64	1.11
10	14.8	26.3	9.6	2.4	7.6	17.6	1.5	3.8	3.3	3.30008	3.8	3.1	0.96	16	0.35	64	1.15
11	9.4	18.4	5.4	2.4	5.3	35.7	3.5	2.1	1.6	1.6417	2.1	1.7	0.96	16	0.35	64	1.27
12	6.5	12.8	2.7	2.7	4.3	60.8	4.9	1.1	0.9	0.86221	1.1	1.1	0.96	16	0.35	64	1.32

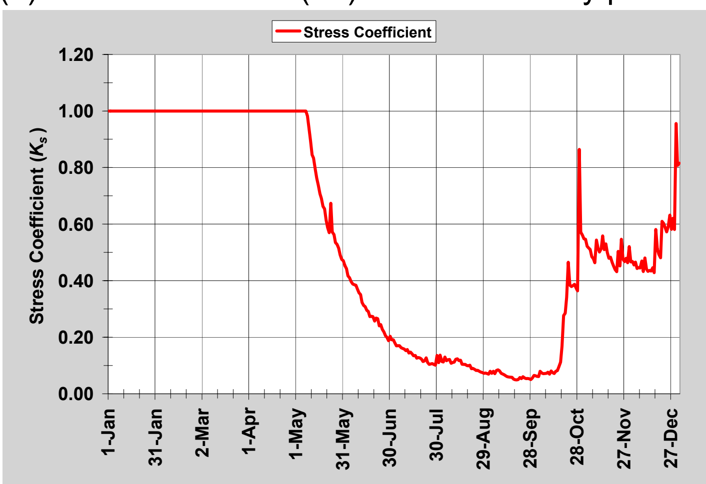
Figure 1. Example of site climatic and plant water use data for Yuba County.

coefficient) factor, which is derived from the graphs of soil moisture (Figure 2 a,b,c) for Yuba, San Diego and Lee Vining. This coefficient remains at 1.0 (maximum evapotranspiration) when adequate moisture remains in the soil, but decreases when soil moisture falls below some pre-determined, soil texture dependent threshold level. These values are measured for a few wildlands plant species by comparing evapotranspiration when plants are under well watered conditions (late winter) compared to droughty conditions. This method allows prediction of plant performance under other site conditions or treatment effects. Evaluation of weather patterns and estimated plant water use for a range of locations statewide would indicate if common trends occur, which would potentially allow a regional-wide specification to be generated. Because of the importance of soil texture for soil water holding capacity functions, the regional value may need to be calibrated for sandy, loamy or clayey substrates.

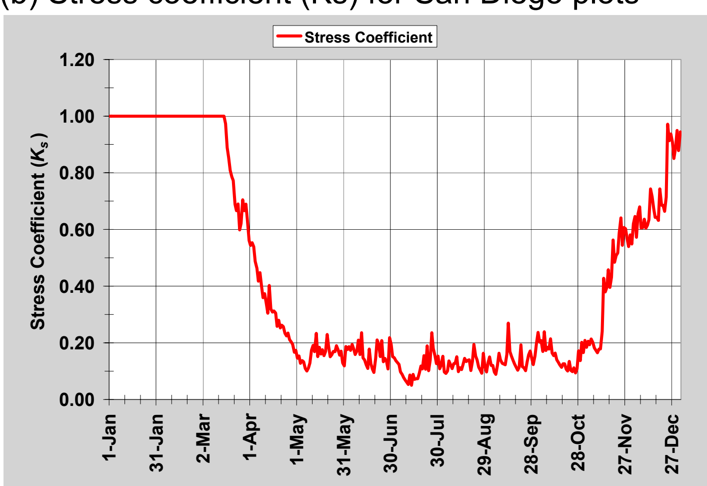
Note that the period of low soil moisture becomes progressively longer between Yuba, San Diego and Lee Vining sites. This indicates that plants are experiencing longer drought conditions in these different regions. The spike in



(a) Stress coefficient (Ks) for Yuba County plots



(b) Stress coefficient (Ks) for San Diego plots



(c) Stress coefficient (Ks) for Lee Vining plots

Figure 2. Stress coefficients for plants growing at three statewide demonstration plots. The length of the lower trace indicates longer droughty conditions.

the San Diego trace indicates an early rain, but continued dry conditions occurred until the soil is re-wetted in late December.

Results and Discussion

Yuba County SR 70

The Yuba County plot results demonstrate that mitigation plants can be grown without irrigation in ambient conditions and that improved rooting volume and plant available moisture is a critical ingredient of this ability (Figure 3). Whereas the Contra Costa SR 4 plots showed a strong positive effect of weed mat protection, the Yuba plots did not. This may result because these clayey substrates become very hard as they dry, which may prevent the swamping effect of adjacent annual weeds on shrub growth.

The ability of roots to rapidly and relatively deeply access lower soil horizons brought statistically significant increases in plant growth. Our expectation that a plastic liner would inhibit even further growth of deep roots was not supported. One possibility is that the liner retained moisture that drained away in the unlined plots.

In spite of the large size of the deep tilled plants, the tops of the shrubs were scorched when monitored in late summer 2008 (Figure 4). This may be caused by planting with too high a density of plant materials, particularly for conditions that develop late in the summer. These plants appeared to overgrow their moisture reserves early in the season, and then experience drought stress later. Nearby plants on wild-land soils did not show this pattern.

The tip die-back could also be caused by poor rooting conditions in the excavated rooting basins. The existing substrate was very poorly drained. During winter, the basins may have filled with water or experienced reduced root health through winter flooding or disease. The uphill shrubs (border row nearest the pavement) were consistently larger and greener than the interior shrubs or lowest border row. This indicates that overland flow may be moving off the road and compacted surface substrate (Figure 5). Low water reserves reduce plant growth when summer comes (Figure 6). If plots flood in winter, plant growth may

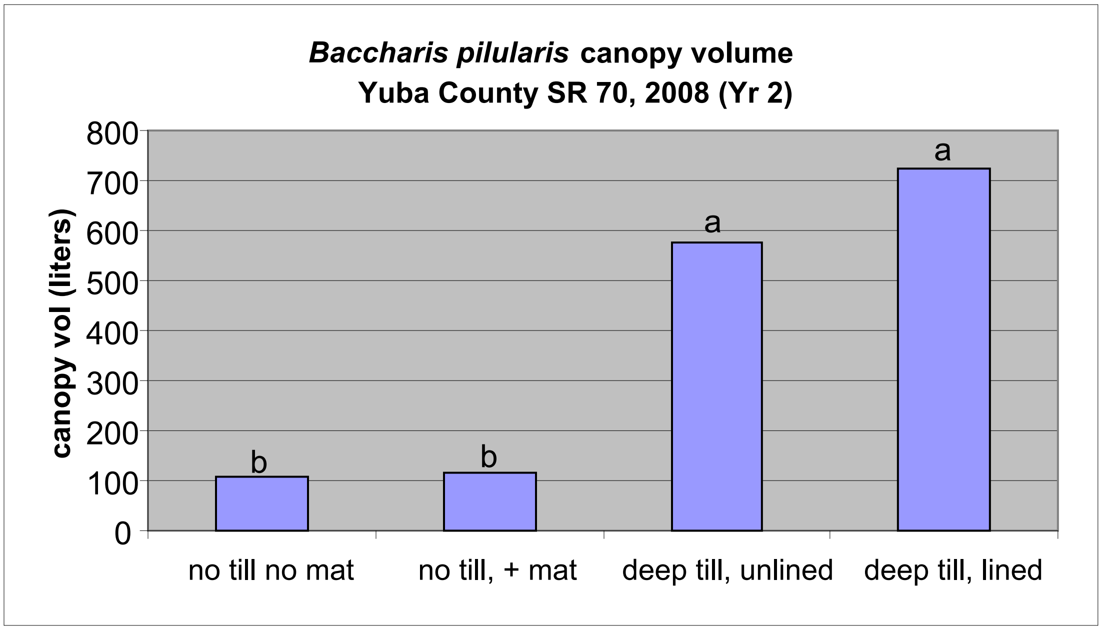


Figure 3. Plant canopy volume from moisture utilization plots from Yuba County. Columns with the same letter do not significantly differ (*p* = 0.10).

Figure 4. Coyote bush plants at Yuba SR 70 in late summer of 2008. Plants have outgrown their water supply during winter and spring and then become scorched during summer. Less dense plant spacing would reduce this effect. Plants in the foreground are on a tilled plot, and smaller plants in background are in a no-till + mat treatment. No irrigation was applied to any plots.

Figure 5. Compacted surface layer of Yuba SR 70 substrate that forms an overhanging ledge (nearest backhoe) and sheets water off the site during rains.

Figure 6. Reduced plant size on mulched plot without tillage at Yuba SR 70.

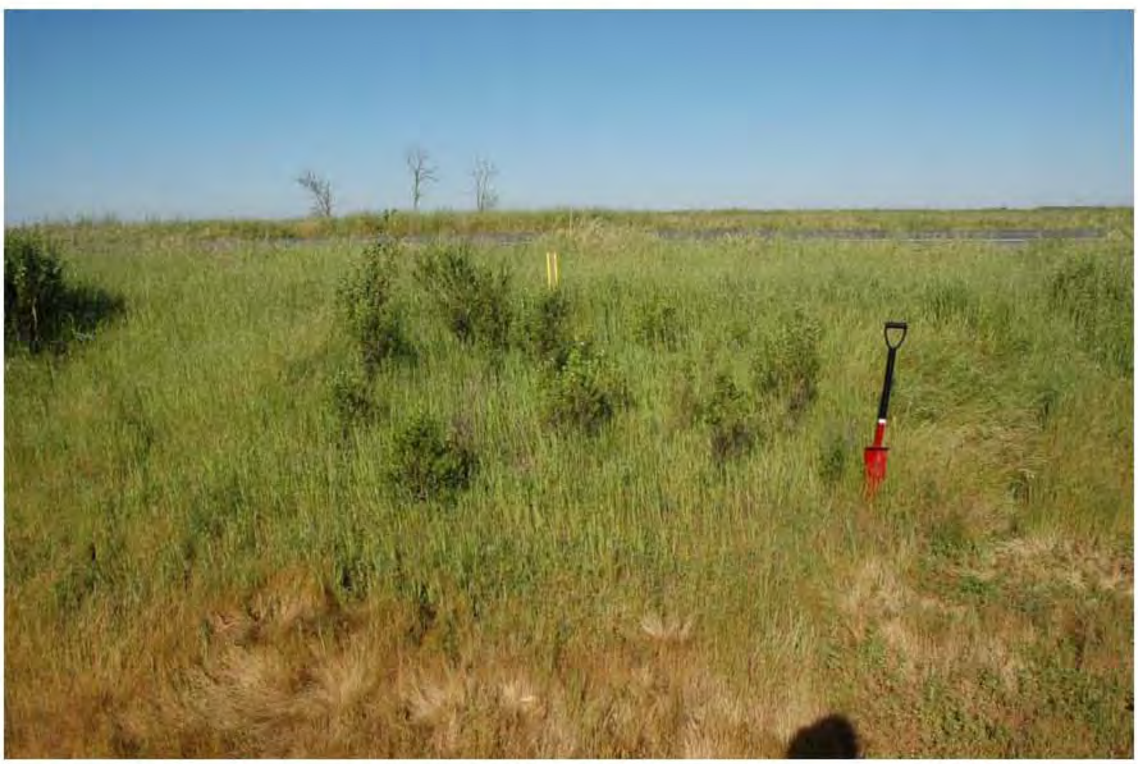


Figure 7 a,b. Recovery of coyote bush (*Baccharis pilularis*) during winter 2009 after drought stress during summer. Plot in top photo is deep tilled to approximately 1 m (3 feet), while the bottom photo shows a plot that received mulch and a weed mat but no soil treatment. No irrigation was ever applied.

Figure 8 a, b. Effect of plot treatment on leaf retention. The top photo was on a deep tilled plot, and retains leaves along the stem. The lower photo shows plants from a non-tilled plot, on which water stress causes leaf abscission during the summer, followed by regrowth from the tip the next winter. Repeated annual water stress results in a long thin stalk (as in Fig 11) without leaves on the lower portion and is often associated with shallow, ”J” shaped roots.

Figure 9. Plant diversity trial at Yuba SR 70 in winter 2009, including California coffeeberry (*Rhamnus californica*), Silver bush lupine (*Lupinus albifrons*), Valley oak (*Quercus lobata*), Blue oak (*Quercus douglassii*), Western redbud (*Cercis occidentalis*), and Buckbrush (*Ceanothus cuneatus*). No irrigation was used. Upper photo in summer 2008, lower photo winter 2009.

be improved because this upper row drains better. Increased soil rooting volume by tillage was visible in increased shrub size (Figure 7) and leaf retention along the stem through the summer season (Figure 8).

San Diego County I-5

The plots from San Diego County also demonstrated that mitigation shrubs can be grown without irrigation (Figure 10). These fine sandy substrates were un-rootable without mechanical decompaction, creating 'J' rooted plants on untreated areas (Figure 11). These plants develop excessively long stems as a result of rapid winter growth followed by consistent dieback of leaves during the summer drought, followed then by regrowth and over-extension the next winter. Tillage alone increased plant growth and tillage plus 10 % compost increased growth further (Figure 12). Top growth of these plants was healthy without the scorch observed in the Yuba plots (Figures 13 and 14).

A tendency of these dispersed, single grain sands and silts may be to settle and re-compact, which was not detected in the short, two year period of this experiment. This effect may be counteracted, however, by robust root growth and continued loading of organics into the soil from on-site plant growth.

Figure 10. View of the San Diego plot location, about 1/4 mile north of Solana Beach exit, I-5 on a bench above the southbound lanes.

Figure 11. Shallow rooting depth creates 'J' rooted plants that can be pulled up singlehandedly. Also note the long bare stems resulting from dieback of summer leaves and regrowth the following winter. San Diego County, I-5 water use plots.

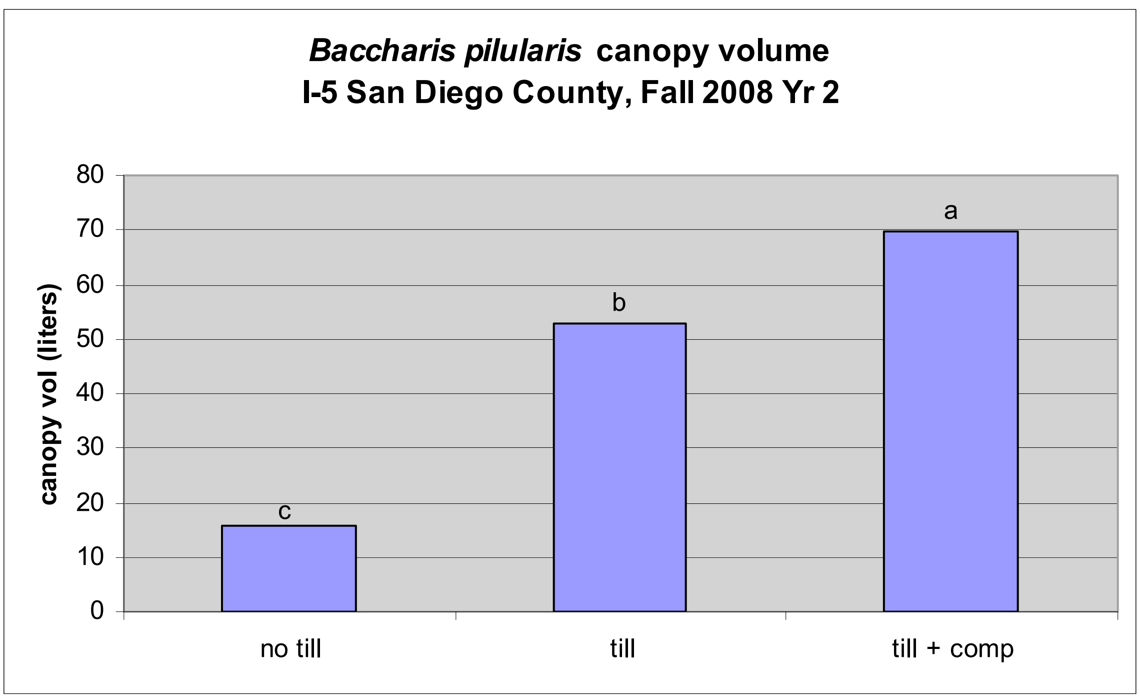


Figure 12. Plant canopy volumes from soil treatment plots at San Diego County. Bars with similar letters do not differ significantly (p = 0.10)

Several other species were planted in a deep tilled, compost amended plot to empirically evaluate other species' growth for biodiversity (Figure 15). Growth was good for the selected species, but canopy measurements were not taken.

One unique aspect of this southern California site compared to the other sites in this study that may influence the greatly increased growth with tillage alone is the occurrence along major traffic arterials and urbanized areas of increased atmospheric deposition of plant available nitrogen. Vourlitis et al. (2007) cite atmospheric deposition in chaparral or coastal sage scrub up to 26.5 kgN/ha/yr. In the San Jose, CA area, low elevation grasslands were estimated to receive 10 - 15 kgN/ha/yr (Weiss, 1999). These are large proportions of the estimated 33 kg N/ha/yr taken up into coastal sage scrub biomass (Gray, 1983). Vigorous vegetative cover can be expected to reverse this trend for a number of years as organic matter and plant biomass and soil organic matter are regenerated on site. Along with reduced sediment losses, this could be a significant contribution of Caltrans revegetation efforts toward improvement of water quality.

Figure 13. Deep tilled plus compost plot after two years, San Diego County, I-5.

Figure 14. Non-tilled plots after two years, San Diego County, I-5.

Figure 15. Plant diversity plot, deep tilled plus compost, including Toyon (*Heteromeles arbutifolia*), Hollyleaf redberry (*Rhamnus ilicifolia*), Bush poppy (*Dendromecon rigida*), Woolyleaf ceanothus (*Ceanothus tomentosus*). San Diego County, I-5.

Lee Vining US 395 Mono County

Plants installed on low intensity, moderately deep plots on the US 395 median showed slow but steady growth. The seedlings installed on deep tilled and compost amendment plots had low survival. Plants along the edge position had the greatest success. Rapid onset of warm weather, common rodent grazing and burrowing or compost salt effects are potential causes. Although seedlings on these tilled volume plots had low survival, the seedlings that did survive were 50 % larger after one year than the pilot scale plot plants were after three years. Even in these droughty conditions, these few surviving plants approached the size of the first year plants of the Yuba and San Diego plots, suggesting that the appropriate soil preparation can generate substantial plant growth even in these arid conditions. Because of the small size and wide spacing (1 m; 3 feet) of these plants, plant-to-plant competition for water was not a likely problem.

The canopy volumes from the low intensity pilot scale plots were smaller than the Yuba and San Diego plots, presumably because of the much lower available rooting volume. The pilot scale plot rooting volumes were only decompacted to about 0.5 to 0.6 m deep by 0.2 m diameter wide (20 to 24 inches x 8 inches). Even with this low intensity treatment, the same trends were observed, with tillage significantly increasing plant growth. The CDE amendment made no significant difference in these conditions. This may result because these materials were amended only to shallow soil depths, which are typically desiccated by evaporation in this environment. Deeper incorporation is recommended to get the benefit of improved water retention that is possible from these materials.

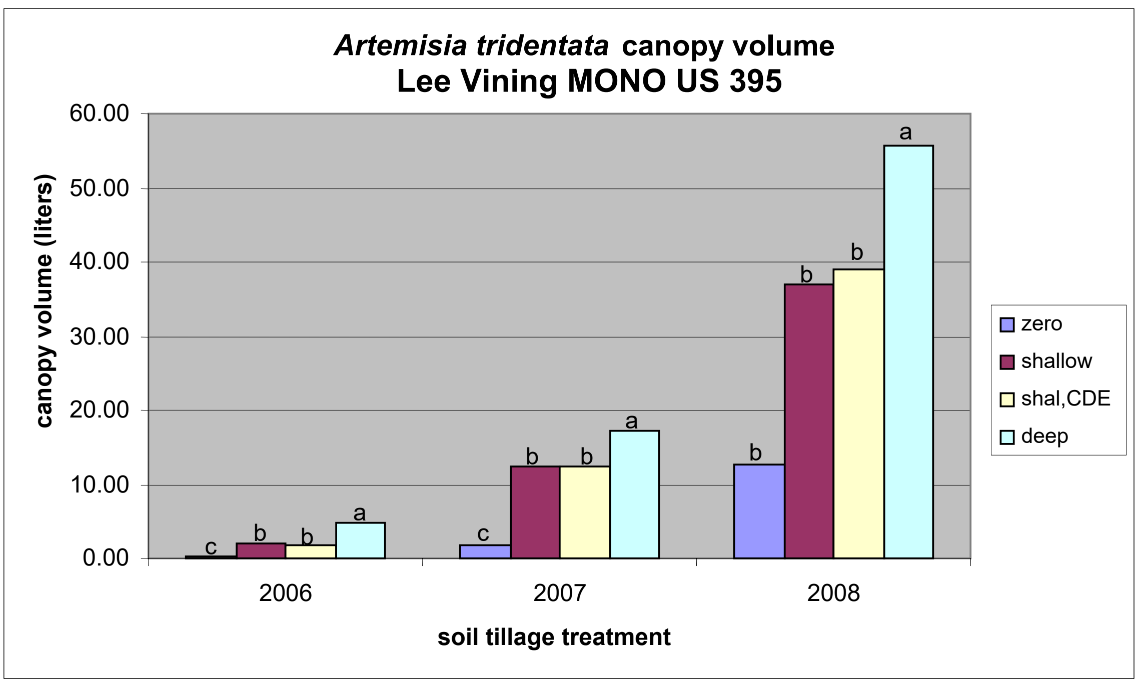


Figure 16. Canopy volume of low intensity pilot scale plots for three years of growth. Bars within each cluster of four bars with similar letters do not differ significantly (p = 0.10).

Figure 17. Three year old *Artemisia tridentata* wthout irrigation.

Growth of sagebrush increased each year regardless of treatment, although plants are relatively small (Figure 16 and 17). Small size makes plants less able to recover from the various disturbances that can occur, including wind scouring of stems, leaves, or removal of substrate around the stem, driving and crushing injury, browsing, or frost heave. Small plants do not contribute greatly to ecosystem function, such as erosion control and aesthetics.

In this area, the predominant plant growth limiting condition is expected to be moisture, and because of the arid, windy environment and low water holding capacity of the substrate, this moisture must be stored deep in a rootable substrate. This argues for a 1 m deep rooting profile (3.3 feet) rather than shallow, scarifiying treatments that do not facilitate deep rooting and that dry rapidly in late spring.

Antelope bitterbrush (*Purshia tridentata*) was only planted on zero tillage and deep tillage treatments. These plants showed the same overall trends in plant canopy growth. Within-treatment variability, however, made treatment differences statistically insignificant. The *p* values were between 0.12 and 0.21,

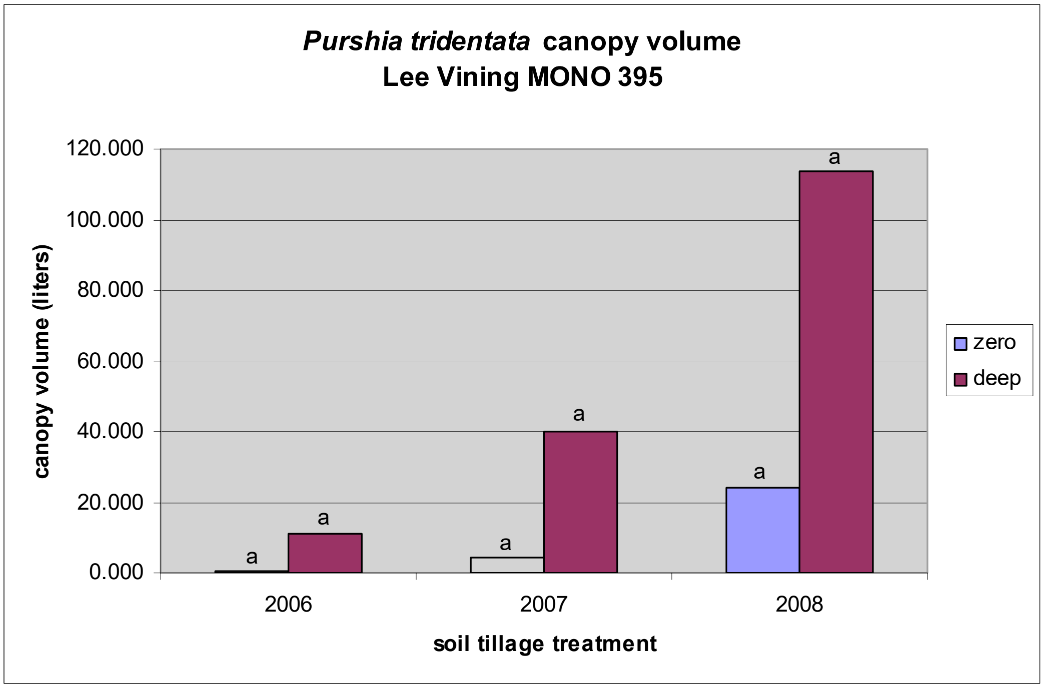


Figure 18. Plant canopy volumes of antelope bitterbrush with no-tillage and deep tillage treatments. Bars within each cluster of two bars with similar letters do not differ significantly (p = 0.10).

Figure 19. Three year old *Purshia tridentata* without irrigation.

suggesting that greater replication or more uniform plant response would yield a numerically significant result, more similar to the observed biological result.

Soil treatments planted to squirreltail (*Elymus elymoides*) showed an opposite trend (Figure 20). First year canopy volume was greater than in second and third years. Surviving plants were heavily grazed. Only the deep tillage treatments showed green basal leaf tissue in the late summer 2008 monitoring; other treatments were either completely missing or showed only dry vegetation above ground. This result confirms the common observation that first year growth responses may not be sustainable and long term monitoring is necessary. Shrubs may be more slower growing but more robust in stressful environments.

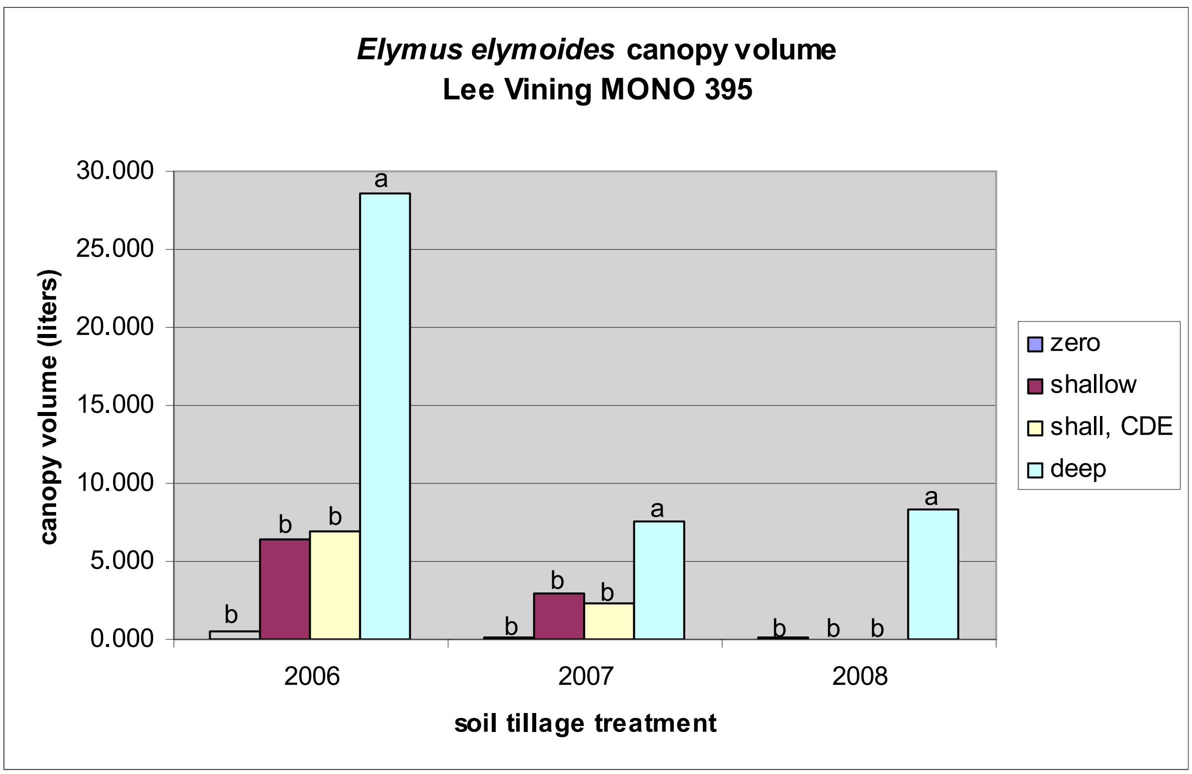


Figure 20. Canopy volume of squirreltail grass. Bars within each cluster of four bars with similar letters do not differ significantly (p = 0.10)

Conclusions

Appropriate soil treatments that increase plant available water were shown to allow shrubs to grow from container-sized plants to large adult plants without supplemental irrigation at four different locations around California. Soil treatments include 1) deep soil tillage to approximately 0.8 to 1 m (3 feet); 2) amendment with yard waste compost of 1 - 2 inches depth tilled into the top 300 mm (12”); 3) assume full wetting of the soil profile by rain by the end of spring before the summer dry season; 4) coverage by a 1 or 2 inch wood chip mulch. For experimental purposes, plants were installed in grids at approximately 1 m (3 foot) on center, representing approximately 20 % cover when plant canopies are 0.5 m (20”) in diameter. Coyote bush plants were used successfully in the Central Valley in northern California and in San Diego County in southern California. Sagebrush was grown successfully for several years in different treatment conditions in arid Mono County, but some plants in a more intensive soil treatment experienced low initial survival either due to predation or compost nutrient / salt effects. This result may indicate that organic amendment is less effective in this dry climate or that the experimental conditions need modification.

Variations of these soil treatments that can be more rapidly mass-produced are recommended. Soil rooting depths can be established by ripping or hydraulic hammer fracturing rather than excavation and replacement, as was done for experimental reasons. Ripping can be done rapidly on field sites, although currently available construction equipment does not incorporate organics deeply into the soil. Weed control is always a concern, and may be addressed by limiting nutrient addition, less intensive soil tillage and heavy mulch applications. Weed control is mandatory for the first two years or more, after which less intensive monitoring and control may be required.

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Appendices

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Appendix Section A. Work Plan.

Research Problem Title: Developing alternative methods/techniques to establish roadside plantings without regular irrigation.
"Alternatives to Irrigation"

Work Plan Outline

Project Objectives
1. Measure plant water use in field conditions
2. Measure content of ambient soils and amended material/soil combinations in the lab
3. Design field installation using promising amendments in Phase 2, with appropriate size and delivery to match the plant water use patterns measured in Phase 1
4. Develop guidelines and recommendations for Caltrans implement when implementing revegetation projects

Deliverables
A. Literature review of plant water use current irrigation practices and Caltrans planting guidelines.
B. Develop a plan for construction and monitoring of all field and laboratory (outdoor garden experiment) trials and test plots.
C. Fall 2005, coordinate with Caltrans and select four (4) potential field sites for installation of test plots.
D. Measure water-holding capacity of soils and amendment materilsl/soil combinations (composts, polymers, clays) in the lab using pressure plate or salt equilibration methods, using substrates from four (4) California locations.
E. First selected field site (CC4).
F. Second selected field sites (YUB70, MONO395, SD xx).
G. Monitor sites
H. Reports and technical articles

Technical basis:
Adequate water use for plant establishment and growth will be provided by a combination of 1) adequate rooting volume and 2) adequate soil water holding capacity.

1) Target values for plant water use will be obtained from garden experiment tests and field measurements of plant water use.
2) Soil rootability will be improved by increasing pore space and fractures for rooting, if needed, and by increasing water holding capacity for plant water retention, if needed.

1. Target values for plant water use
Plant water use is difficult to determine for wildlands plants under field conditions. Methods have involved lysimeters (large containers) whose water content is determined by large scales, or by instruments (TDR probes, psychrometers) that indicate water content by measuring a smaller volume of soil or that indicate water content by the dryness of the soil volume.

Field soil volumes are difficult to measure because they have scattered rocks and variable soil textures. At CC4 mile 7.2 we have had to modify our plan for using the neutron probe because of 1) the difficulty of installing the 2 inch PVC tubes into the rocky soil and 2) the difficulty of extracting representative soil volumes for calibration of the neutron probe without disrupting plant roots.

Our proposal is to measure plant water use in specially prepared, homogenized soil volumes, using TDR probes and stem flow moisture sensors.

Finally, plant water use changes greatly with the availability of moisture in the soil. When soils have easily available moisture, they often use greater amounts. When the soil's moisture is held more tightly, the plants commonly decrease the amount of water they use. Therefore, the amount of water needed to allow a plant to survive the summer drought often changes with the amount of water available to be used. Plants tend to use all the water available to them, and plants in drier soils grow smaller and slower.

1. Site selection criteria

Prospective sites shall:

1) have conditions causing water stress in plants

Sites must have some characteristic that is relevant to the problem of providing soil moisture as a substitute for irrigation for plant establishment. For example, sites with shallow soil should be made deeper, or coarse textured sites should be made more water retentive, or sites that have poor infiltration should be made more porous. Plants should be used that can tolerate extended periods of water stress and access the residual water in the soil profile.

2) be representative of common Caltrans revegetation challenges with reduced use of irrigation

Sites must be relevant to general Caltrans problems or be applicable to other common Caltrans sites that have had plant establishment problems related to lack of plant-available water. These problems may be geological based (rock type), topographically based (slope position, shallow soil) or design/construction based (compacted subgrade horizons, shallow rooting depth after construction)

3) be of experimental quality (uniform for replications and stable for long term observations)

Sites must be uniform enough that experimental work can be installed, meaning that replicated plots are all on similar substrates. They must be in an area that is protected enough that multi-year (3 yr) monitoring can be completed and so that long-term effects (5 - 10 years) can be observed as the plants mature.

4) utilize native wildlands species

Because summer drought conditions include extended periods of drought, this project will involve plants that are adapted to these conditions and are not invasive. Horticultural plant species that are dependent on constant irrigation are not considered in this project.

5) represent one of four selected California regions

Sites will be located in 1) central valley (Contra Costa site), 2) east side of the Sierra Nevada (395 area), 3) coastal conditions and 4) southern California.

6) not have overriding harsh site conditions other than moisture availability

Sites with steep, unstable geology, no soil, toxic conditions, or pervasive lack of nutrients will not be considered for this ATI project because these harsh sites require a more complete overhaul of the substrate and will be considered in other work, such as the Soil Resource Evaluation project.

Site development sequence

Evaluating water use on road-cuts

Field plots:
At four locations in California (HW 4 near Martinez, HW 395 near Mono Lake, HW 70 near Sutter, and somewhere in San Diego)
Soil screened to < 25 of 64 mm
Plot size 1.5 x 1.5 m and 2 m deep
Planted with Coyote bush 70 cm on center (4 per plot)
TDT moisture probes place in center of shrubs at the following depths:
20, 40, 60, 80, 100, 130, 160, 200 cm
The moisture values will be logged every day at 8 pm
There will be 3-4 replicates
A nearby weather station will provide daily and monthly ETo estimates (in some cases on site weather stations may be required)
Use ATM's program to adjust for aspect, slope and plant height.

Second set of plots that are only 0.5 m deep (20, 40 cm probe depth)
Place plastic on bottom of plots for these shallow plots to limit soil resource and stress out these plants.

Data gathered from plots:
Daily, monthly and season ETa from plots
Rooting depth may be determined by augering into plot at the end of season
Maximum pre-dawn and mid-day potentials may be determined in the fall before the rains
Biomass, leaf area, plant volume at end of season (compare water use to plant growth)
Plant height and % cover every month through growing season

So what:
Develop crop coefficients, and monthly stress coefficients for coyote bush given the measured ETa and the theoretical ETo.
Compare crop coefficients developed for coyote bush at four locations around state to see if coefficients are consistent.
Compare growth and water use of plants growing on deep and shallow plots to look at gradient.
Did crop coefficients (water use) from field sites compare with those developed by the pot study?
If a relationship between ETo and coyote brush water use can be established then recommend that the state ETo map be used to spec the soil water resource requirements as related to soil depth and necessary amendments.

Appendix Section B. Literature review of plant water use

Synopsis

This section reviews the basic processes of plant water use and published literature from other research projects involving water use of wild-land plants in non-irrigated conditions.

Introduction

Determining the water use of wild-land plants is of great practical importance in order to ensure the long-term success of revegetation efforts. Plant water use availability affects revegetation planting success in several ways. First, if water is limiting, mitigation plantings will develop greater plant-to-plant spacing as they mature. This may reduce plant density below target thresholds. Selection of mitigation sites on soils that are inherently too shallow may also compromise the ultimate success of the project. Soil water availability should be predictable to select alternative sites that are more adequate. If the planting is to be done on disturbed soils, water availability is very often limiting because these materials generally consist of unconsolidated parent materials that are often low in clay and organic matter content, resulting in a low water holding capacity.

The amount of water that is useful to plants is defined as the difference in water content between saturated soils that have drained due to gravitational pull, called field capacity (FC) and the water left in the soil when the plant has wilted and cannot extract additional moisture. This last condition is called permanent wilting point (PWP). PWP varies by plant species, but for agricultural crops it is stereotypically set at -15 bar tension (-1.5 MPa, or -1500 J/kg). In arid environments, the amount of plant available water (PAW) in a soil can be the most limiting factor to plant growth. If the water needs of a desired plant community are known, then the soil or substrate can be selected or treated to have an adequate water holding capacity to sustain the plant community from year to year. This is especially true in California's Mediterranean (summer dry) climate.

This section provides a review of the literature concerning seasonal wild-land plant water use from a variety of locations, soil types, slopes, aspects, and nutrient regimes. The review was intended to identify the range of plant water use across various soil and climatic conditions. These data are used to provide a general guideline for total plant water use.

Four general plant types were identified: annual grasses, perennial grasses, shrubs, and trees. Reported water use values for each plant type have been grouped together for the purpose of determining if there are water use ranges, characteristic of the four general plant types. All the reviewed plant types can be found in California, but again, each reported value must be carefully interpreted to account for site specific climatic and substrate (geological) peculiarities, as well as artifacts of different measurement methods.

Methods used to determine water use

The methods used to determine plant water use in the reviewed literature can be divided into two general groups, including measured soil moisture depletion (decrease of water content in soil during a time period), and water budget estimates (expected water use based on seasonal weather patterns). Soil moisture depletion over a growing season was the most common method of evaluating plant water use. The water budget method, both seasonal and annual, was used in lysimeter studies as well as for an entire watershed. Within each of the above-mentioned methods, the specific approach varied with each study. Therefore, target values are heavily interpretive.

In order to determine soil moisture depletion, the initial moisture content of the soil was measured before the target growing season. For summer water use in California, this would be after the last rains when the soil is at field capacity (around May). At the end of the growing season or just before the first rains in the fall, the soil moisture content was measured again. The difference between these two soil water measurements was estimated to be the amount of water removed by evapo-transpiration during the growing season

Typically, soil moisture was not measured below two meters. Depending on the plant type this may not be deep enough to account for the entire zone of root influence. Some perennial grasses and many shrubs and trees have root systems which extend well below two meters. Oak trees have been shown to have roots that extend down to 24 meters (78 feet) (Lewis et al. 1963). However, the majority of roots (regardless of plant type) are located in the top two meters (six feet) of soil, and the relative contribution of deeper roots to the plants total water use is beyond the scope of this review. It is sufficient to say that in regards to perennial grasses, shrubs and trees the soil moisture depletion method may underestimate the plants actual water use since it usually only accounts for the water used in the top 2 m. The top 2 m (6 ft) does, however, account for the majority of soil moisture used in the first few years of establishment.

Soil moisture depletion was measured in four ways: neutron probes, electrical resistance (including Coleman blocks), and gravimetric weights. Each of these techniques requires that soil cores or loose samples be removed from the study site and water release curves characterized. The removal of soil cores can prove to be a difficult task. In rocky or shallow soils, the soil structure may be altered during sampling of soil cores. Further, the heterogeneity of these soils makes it difficult to collect enough cores to characterize the soil within a reasonable degree of accuracy.

Two other possible sources of error when determining water use by moisture depletion come from surface evaporation, and summer precipitation. Soils that lack shading, a mulch layer or surface crust may lose a significant proportion of their moisture from the surface due to evaporation. The same plant type may have drastically different seasonal water use depending on the evaporative demand over the season for mulched or unmulched sites. Rainfall events occurring after the initial soil moisture content was determined are not included in the seasonal water use unless the data were adjusted. Not accounting for summer rainfall may result in artificially low seasonal water use values. Despite the above-mentioned challenges associated with measuring soil moisture depletion, this method provides one of the most accurate ways to determine water use under natural conditions.

The water budget method assumes a system where the inputs and the outputs are either controlled or at least known. Lysimeters are large weighing containers in which plants are grown. The loss of weight over a given time represents evapo-transpiration. Control lysimeters without any plants can be used to factor out any loss of water due to surface evaporation, and the actual plant water use can then be determined. Furthermore, the influence of summer precipitation can be determined and factored out of the plants water use. In addition to seasonal water use, lysimeters may be used to measure annual water use as well.

Lysimeters are filled with a given soil type and allowed to settle over a several year period. This process creates an artifact in that the soil has been disturbed. Great effort has been put into determining the accuracy of lysimeters in representing natural conditions. From the reported values examined in this paper, it is difficult to compare lysimeter values with soil moisture depletion values since lysimeter studies report the annual water use and soil moisture depletion only measures seasonal water use (Table 1).

The largest scale of water use measurement in this review is on a watershed level. The water budget for a watershed consists of inputs (precipitation + baseflow) that annually equal outputs (evapotranspiraion + deep percolation + stream flow). Deep percolation is difficult to measure and is often assumed to be negligible. This assumption may lead to an overestimate in plant water use.

Watersheds usually consist of more than one plant type, so the water use values represent an integration of an ecosystem of plant types. Studies at the watershed level are a monumental task since they require long-term data collection. In light of this fact only one relevant watershed study was found to include in this review. This method gives the annual water use in the watershed, and when compared to the annual water use values from lysimeter studies they were similar.

Summary of References

The following are brief summaries of the references used to evaluate water use by wild-land plants. Many of these studies were designed to ask very different types of questions and had to be re-interpreted for their relationship to plant water use. Therefore, the entirety of these papers is not presented, however all of the data useful for this topic is covered. The references in Table 1 can be found in the 'water use and soil moisture' section below.

1) Cline et al., 1977, used the soil moisture depletion method to evaluate differences in seasonal water use in both abandoned wheat fields where *Bromus tectorum* (cheatgrass) was the dominant grass species, and a native reference site where perennial grasses dominated. The study was carried out in south-central Washington. Cheatgrass was found to use 80 mm (3.1 inches) of water over the growing season. This value represents the low end of the reported water use values for annual grasses. It only exploited water from the top 0.5 meters (18 inches) of the soil, while bluebunch wheatgrass exploited water to a depth of well over a meter (39 inches). The greater rooting depth of the perennials allowed them access to water throughout the summer. The bunchgrass community used 150 mm (6 in) of water over the summer months.

2) Rowe and Reimann (1961) used soil moisture depletion to evaluate differences in water use between annual grass, annual grass-forb, and oak brush communities. The study site was located in the San Gabriel Mountains in southern California. The annual grass was *Lolium multiflorum* (Italian ryegrass), and it used 177 mm of water over the dry season (April-October). The annual grass-forb cover used 201 mm, and the oak brush used 330mm of water over the dry season. The annual grass exploited water to 0.66 meters, the annual grass-forbs exploited water to 1.52 meters, and the oak brush exploited water to 3.66 meters. This study represented five years of data collection.

3) In western Colorado, Brown and Thompson (1965) examined differences in water use between mountain grasslands, aspens and spruce plots. Soil moisture depletion in the top 2.44 meters was used to measure water use, and then adjusted for summer precipitation. This study was carried out over a three-year period. The grassland was dominated by perennials (Idaho fescue, Letterman needlegrass, Thurber fescue, Freemont geranium, and hairy goldaster), and had a seasonal water use of 226 mm. The aspens used 488 mm of water, and the spruce used 378mm. Nearly all the water used by the grassland was from the top 1.22 meters of soil. However, both the aspens and the spruce exploited water to the full measured depth.

4) In Placer County, California, Lewis and Burgy (1963) used soil moisture depletion to evaluate water use by annual grasses. These values were used in part to calibrate lysimeters, and the Coleman blocks that were placed inside two five-foot floating lysimeters. From April to June the water use of the grass was found to be 122 mm after being adjusted for summer rain. The lysimeters were in general agreement with the Coleman blocks.

5) Patric (1961) used lysimeters in the San Gabriel Mountains in southern California to evaluate water use in perennial grasses (*Stipa lepida Hitchc., Poa scabrella (Thurb.) Benth.* etc.), scrub oak (*Quercus domosa*), and ceanothus (*Ceanothus crassifolius*). This study measured water use for the entire year, so these values cannot be directly compared with seasonal water use values. The perennial grasses used 399 mm of water over the year, while the scrub oak used 457mm and the ceanothus used 455 mm. The lysimeters were 10.5 feet wide, 20.8 feet long, and 6 feet deep. The woody plants used all the available moisture in the lysimeter during the dry season, however the grass had water available in the lysimeter throughout the year.

6) Yoder and Nowak (1999) used neutron probes to determine the water use of two types of shrubs in the Mojave Desert. Water use by evergreen and drought-

deciduous shrubs was measured during wet and dry years. Depending on how much moisture was available in the soil both shrubs used between 50-230mm of water each year. These are highly specialized plant communities and that are able to tolerate quite harsh conditions as well as take advantage of favorable conditions. Although, the shrub communities only used 50mm of water in a dry year, it would be presumptuous to think that this represents a sustainable lower limit. Multiple years of data from this type of drought could determine if this was the case, or if plants were dying back in these conditions. In addition, the neutron probes could only be placed to a maximum depth of 2 meters, and these shrubs may very well have roots that extend well beyond this depth (although most roots were located in the top 0.5 meters of the soil).

It is important to note that soil moisture depletion directly under the plant did not vary from soil moisture depletion between plants in this study. Shrubs were a minimum of 1 meter apart from each other. This indicates a well-developed lateral rooting system, which may necessitate spacing requirements for adequate water availability.

7) An ambitious 17-year study in the western foothills of the Sierra-Nevada measured the water budget of an oak woodland watershed (Lewis et al. 2000) to generate long-term water use data. The oak woodland is a mosaic of scattered oaks and annual grasslands. The average water use of the watershed over 17 years was 368mm. This may underestimate the actual water use since base flow continued long after the last precipitation event. The base flow may have been due to deep cracks contributing to the water budget (Lewis and Bergy 1964), or perhaps lateral flow in saturated soil horizons.

8) Breda et al. (1993) examined the water use of a mature oak stand (*Quercus petraea*) in northeastern France. Neutron probes were used to measure soil moisture depletion to a depth of 1.6 meters. This study was conducted over two summers that were unusually dry, with the average water use for the oaks being

153mm. Trenches were dug around eight trees to inhibit lateral flow, and plastic was used to cover the ground so the soil wasn't recharged by rain. Although oak roots have been shown to extend well beyond 1.2 meters, there was a strong clay horizon at 70cm that seriously impeded vertical root growth.

Conclusions

Annual grass summer water use was shown to range from 80-201 mm (Table 1), with a general rooting depth of less than 0.3 m, although some species may exploit water down to 0.6 m. Water use of perennial grasses ranged from 150-399 mm, with roots penetrating often below 1 m. Shrub water use ranged from 50-457 mm during the summer growing season. The 50 mm water use value was specific to a desert shrub in a drought year. Shrub roots have been shown to extend to 3.7 m, and may exploit water in the cracks of the bedrock. Water use by trees ranged anywhere from 153-488 mm of water during a year or growing season. Rooting depth is highly variable between species, but generally between 1-5 meters. Tree roots were shown to be highly effective at utilizing all the available water in the soil to the lowest depth of influence.

General threshold values of water use of annual grasses, perennial grasses, shrubs, and trees may help to determine the plant types suitable for a given site. This however, would at best be a rough estimation and could not prescribe a desired plant coverage, as is often necessary for mitigation purposes. The general amounts of water measured do, however, indicate how much soil water holding capacity is needed for general types of plants to survive.

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Table 1: Water use of four plant types

Plant type	ET (mm)	Method	Root Zone (cm)	Soil Type	Landscape/Aspect	Location	Reference
1) cheatgrass (Bromus tectorum)	80	soil moisture depletion*	0-50*****	silt-loam	east-facing gentle slope	south-central WA	Cline et al (1977)
2) annual grasses	122	soil moisture depltetion**	no data	no data	flat	Placer County, CA	Lewis et al (1963)
3) Italian ryegrass (Lolium multiflorum)	177	soil moisture depletion***	0-66*****	stony, sandy-loam	east-facing, 35% gradient	San Dimas, CA	Rowe et al (1961)
4) Italian ryegrass/forbs (Stephanomaria virgata etc.)	201	soil moisture depletion***	0-152*****	stony, sandy-loam	east-facing, 35% gradient	San Dimas, CA	Rowe et al (1961)
5) bunchgrass community	150	soil moisture depletion****	0-160*****	silt-loam	east-facing gentle slope	south-central WA	Cline et al (1977)
6) perennial grasses (Idaho fescue, etc.)	226	soil moisture depletion****	0-122	grey wooded podsol	15% or less average	Black Mesa, CO	Brown et al (1965)
7) perennial grasses (Stipa lepida hitchc. etc.)	399	lysimeter	0-122*****	sandy, clay-loam	5%	San Dimas, CA	Patric et al (1961)
8) chaparral(scrub oak, birch leaf mount. Mahogany etc.)	330	soil moisture depletion***	0-366*****	stony, sandy-loam	east-facing, 35% gradient	San Dimas, CA	Rowe et al (1961)
9) scrub oaks (Quercus dumosa Nutt.)	457	lysimeter	0-183*****	sandy, clay-loam	5%	San Dimas, CA	Patric et al (1961)
10) Hoaryleaf ceanothus (Ceanothus crassifolius Torr.)	455	lysimeter	0-183*****	sandy, clay-loam	5%	San Dimas, CA	Patric et al (1961)
11) evergreen and drought deciduous shrubs	50-230	soil moisture depletion*	115-greater than 195	Entisols w/ an ochric epipedon	no data	Mojave Desert, NV	Yoder et al (1999)
12) oak woodland/annual grassland	368	water balance	no data	Ruptic-Lithic Xerochrepts, Mollic Haploxeralfs	18% average	Yuba County, CA	Lewis et al (2000)
13) oak stand (Quercus petraea, 32 yr.old stand)	153	soil moisture depletion*	0-140	Gleyic Luvisol	no data	Seichamps, FR	Breda et al (1993)
14) quaking aspen	488	soil moisture depletion***	0-244	grey wooded podsol	15% or less	Black Mesa, CO	Brown et al (1965)
15) englemann spruce	378	soil moisture depletion***	0-244	grey wooded podsol	15% or less	Black Mesa, CO	Brown et al (1965)

* neutron probe, ** Colman blocks, ***determined by means of electrical resistance,**** determined gravimetrically, ***** depth to which soil potential reached > or = to -1.5 MPa

Notes:

1) ET during dry season~April to October
2) ET for one dry season ~April-June, Colman blocks in four foot lysimeter
3) ET was average of three years during dry season ~April to November
4) ET for one dry season ~May-December (204 days)
5) ET during dry season~April to October
6) ET for dry season ~June-October
7) ET was for entire year
8) ET was an average of five years during the dry season~April-October
9) ET was for entire year
10) ET was for entire year
11) ET was for entire year, low ET was a drought year, high ET was a wet year, shrubs spaced approx. 2 m apart, most roots were found in the top 0.5 meter
12) ET was 17 year annual average, 85% grass roots in top 10 cm.
13) Low ET was in a dry year, high ET was normal year, 75% of roots were in the top 60 cm
14) ET for dry season ~June-October
15) ET for dry season ~June-October

ET values determined by soil moisture depletion for perennials, shrubs, and trees may be erroneously low depending on soil texture and depth. This method is limited by the depth of sampling, and may not account for roots (as sparse as they may be) penetrating beyond that depth. For all root depth measurements, values must be interpreted with great care in terms of site specific conditions. Shrub roots may penetrate a few meters, and some trees (oaks) have been shown to have roots in excess of 24 meters (Lewis et al, 1963).

Appendix Section C. Literature Review of Plant Available Water in Inorganic Amendments and Polymers:

Synopsis

This section reviews background information on the ability of soil amendments (inorganic amendments and polymers) to change the amount of water available for plant growth. All amendments held water, but not necessarily in a way that would benefit wild-land plants. Inorganic amendments are recommended over organic polymers for field conditions.

Introduction

In some cases, the amount of water needed by a desired plant type and a shallow soil depth or coarse texture at the site location may mean that more moisture is required by the plant than can be stored in the existing soil material. In this case, amendments are needed that improve soil water content. A review of the water holding capacity characteristics of inorganic amendments (IAs) and organic polymers was performed.

Most of the studies report amount of water held at a given negative pressure (suction). These negative pressures in plant and soils are called matric potentials, and indicate how strongly water is being pulled away from the plant or soil. Liquid water is said to have zero matric potential, or -0.0 megaPascals (MPa). Gravity drains water out of soils at a matric potential of about -0.01 MPa (for sands) to -0.03 MPa (-1/3 bar)(for loams). Agronomic crops are stereotypically viewed to wilt at -1.5 MPa (-15 bars). Wild-land plants, however, can pull water out of soil to -2.0 to -5.0 MPa and some are measured at -7.0 MPa. The amount of water held in a soil amendment is evaluated for the matric tension needed to withdraw it. Ecologically, the amendment should store water until wild-land plants extract it at matric potentials more negative than - 2 or 3 MPa, or else the moisture will be used up early in the season and not be available to help plants survive later in the drought.

Inorganic amendments are those materials made up of clays that have been stabilized by thermal transformation (calcine or fritting processes). Polymers are very large organic molecules that are hydrophilic (attract and retain water) and can hold up to hundreds of times their dry weight when wet. The following are summaries of studies that examined the water holding properties of these substrates.

Summary of references

Inorganic amendments (IAs)

1) Bigelow et al., 2004 examined the water holding properties of four IAs. Their objective was to find a substitute for using peat moss to increase plant available water (PAW) in golf greens. They examined zeolite, vitrified clay, diatomaceous earth and calcined clay at two application rates (10 and 20 % by volume). They added these IAs to three size classes of sands: fine (0.1 mm diam.), medium (0.25 mm diam.), and coarse (0.5 mm diam.) sand. They found that between 0 and -0.006 MPa about 30 % of the “available” water between saturation and PWP was held. This is very wet soil by wildlands standards. No IA held as much water as the peat moss but they did note that diatomaceous earth and calcined clay held more PAW than the other IAs. They also reported a decrease in PAW in fine sands amended with IA, probably because of larger pores with or between IA particles and the fine sands. In order for the IA to be effective, its PAW needs to be greater than the soil it is amending. A considerable amount of water was found to be held in IA at matric potentials more negative than -0.1 MPa. Wild-land plants usually extract water far below (more droughty than) this matric potential. Water held more tightly will be more slowly available from that IA and may help the plants to regulate water use during the summer dry-down. Technical details of methods are also important. Researchers found that plant roots were able to extract more water from IA amended sands at a given matric potential than was estimated from lab methods using pressure plate extractions.

2) This study (Li et al., 2000) also examined the influence of IAs on the water holding properties of sand-based sports turf. Ceramic, porous ceramic clay, calcined diatomaceous earth and polymer coated clays were examined. They mixed the IAs at 10% (v/v). They only measured water release at very wet matric potentials (near 0) with a minimum matric potential of -0.3 MPa. This is would be perceived as a "damp" soil, so these are not droughty moisture reserves. They found that all available water was held between -0.001 and -0.01 MPa. This study only measured the water release of water held between IA/sand particles and did not take into account the amount of water held internally in IAs.

3) van Bavel et al. (1978) examined the water holding properties of fritted (calcined) clay. They did not mix it with any soil. They used granules between 1 and 2 mm in diameter. The PAW content was reported in g/g. Between -0.01 and -1.5 MPa fritted clay was shown to hold ~22 % PAW. A much higher PAW (31 %) was reported but that included water that was held above -0.01 MPa. This study also shows that IA hold considerable water at low matric potentials.

4) Waltz et al. (2003) examined the ability of calcined clay, diatomaceous earth and peat moss to increase the water holding properties of quartz sand. They mixed the IAs at 15 % by volume with the sand. At matric potentials less negative than -0.005 MPa, the IAs increased the water holding capacity of the sand by ~4 %. They did not examine the water holding properties below -0.005 MPa. They concluded that diatomaceous earth behaved most similar to peat moss in terms of water holding capacity.

Polymers

5) Polyacrylamide (PAM) gels were added to a sandy soil to increase the PAW content of the soil (Azzam, 1983). Dosages of PAM ranged from 12.5 mg/100 g soil to 500 mg/100 g soil. The lowest dosage increased the PAW of the sand by 2.4 times and the highest dosage increased the PAW of the sand by 5.75 times. They also found no negative effects of PAM on seed germination.

6) Baasari et al. (1986) added a PAM named 'Aquastock') to a sandy loam soil and evaluated its influence on water holding capacity. This study did not specify the application rate. The bulk density of the PAM was stated to be 0.85 g/ml. The PAW content was increased by 4 % (v/v) after 6 wetting and drying cycles. There was a decrease in the PAMs ability to increase PAW with wetting and drying cycles. When the PAM was mixed in the soil of a potted plant it required 35 % less irrigation. They concluded that Aquastock is a valuable tool but also very expensive and its ability to increase PAW would be limited to a season.

7) Choudhary et al. (1995) examined four PAM soil conditioners at three application rates applied to a sand and loam soil. The PAMs were 'Broadleaf,' 'Agrihope,' 'Aquasorb' and 'Hydrogel.' They applied the PAMs at 0, 0.2, 0.4 and 0.6 % on a dry mass basis. After 16 wetting and drying cycles they found that water holding capacity of the samples increased with increasing PAM application. In order of efficacy of increasing water holding capacity at field capacity they found Broadleaf>Aquasorb>Agrihope>Hydrogel. They also noted that PAM application reduced evapo-transpiration. They did not attempt to evaluate water holding properties at -1.5 MPa (PWP) so it is impossible to determine the amount of PAW in each PAM.

8) Geesing and Schmidhalter (2004) applied three rates of a PAM to three soils and evaluated the water holding properties of these combinations. Soils were loam, silty clay loam and sandy loam and application rates of PAM were 0, 1, 3 and 5 g/liter of soil. They found that an application rate of PAM at 3 g/liter of soil increased water holding capacity in soils at matric potentials above -0.1 MPa. The effectiveness of this PAM to increase water holding capacity decreased with repeated wetting. They also looked at the influence of PAM on wheat and found that there was an increase in sodium content in the grain with increased PAM use.

9) The PAM called ‘super slurper’ was evaluated by Hemyari and Nofiziger (1981) for its ability to increase water retention in three soils. They applied this PAM at rates of 0, 0.025, 0.05, 0.1, 0.2 and 0.4 % by dry weight. The soils they amended were a sandy loam, clay loam and a loamy sand. They found an increase in PAW in the loamy sand and sandy loam with 0.2 and 0.4 % application rates, where the control held 3 % PAW, the 0.2 % treatment held 5 % PAW and the 0.4 % treatment held 9 % PAW. Only the 0.4 % treatment increased PAW in the clay loam. Soil texture was shown to determine whether a PAM will increase PAW. Coarse textured soils will benefit more from PAM amendments since they have a very low inherent PAW content. No attempt was made to determine how repeated wetting and drying cycles would influence PAW contents. They found that most water was released from the PAM by -0.05 MPa.

10) Nimah et al. (1983) examined changes in water holding properties of a sandy loam and a clay soil when they were amended with ‘Hydromull’ and ‘Agrisil.’ Hydromull is a ureaformaldehyde foam that comes in flake form and Agrisil is an amorphous sodium silicate. Hydromull was applied at 200 m^3/ha and Agrisil at 2 tons/ha. In the sandy loam the PAW was increased over two times in the hydromull treatment (9.7 vs 4.3 %) and increased by ~50 % in the Agrisil treatment (6.4 vs 4.3 %). Both soil conditioners increased PAW in the clay soil but to a lesser extent. The PAW values were determined after six wetting and drying cycles. They found that most of the water held by the conditioners was held between 0 and -0.5 MPa. Hydromull only became fully saturated after four wetting and drying cycles but produced the greatest amount of PAW. It was also noted that Hydromull may tend to be blown away when applied as a foam.

Conclusions

Inorganic amendments were shown to hold considerable water near saturation due to their porosity. They also had plant-available water contents from between 17-31 %, but most studies evaluated only the wet end of the soil moisture range. The van Bavel et al (1978) study was an important exception that evaluated drier soil conditions. The polymers also held water in the plant available range. Their effectiveness decreased over time, however, as ions (mainly calcium) from the soil bound and cross-linked with the polymers. For this reason, inorganic amendments are suggested as a long-lasting soil amendment that would help to reduce irrigation, whereas polymers are not sufficiently long-lasting in field soil conditions and would need repeated application. The performance of these materials under common, wild-land conditions was not evaluated in these reviewed studies.

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Amendment Type	Application Rate	Study Soil	Near Saturation	Near PWP	PAW	Reference
Synthetic polymers						
PAM gel	12.5-300mg/100 g soil	Sandy soil			2.5 to 5.75 fold increase	Azzam, R.A.I. 1983
PAM 'aquastock'	not determined	Sandy loam			4 % v/v after 6 WDC	Baasari et al., 1986
PAM 'Broadleaf P4'	0,.2,.4,.6% on dw basis	Sand and Loam	0.6% 200% WHC			Choudhary et al., 1995
PAM 'Agrihope'	0,.2,.4,.6% on dw basis	Sand and Loam	0.6% 160% inc			Choudhary et al., 1996
PAM 'Aquasorb'	0,.2,.4,.6% on dw basis	Sand and Loam	0.6% 195 % inc			Choudhary et al., 1997
PAM 'Hydrogel'	0,.2,.4,.6% on dw basis	Sand and Loam	0.6% 150 % inc			Choudhary et al., 1998
Na-PAM	0,1,3,5 g/liter soil	S lm, lm, si cl lm	5 g/l inc. by 2%v/v			Geesing et al., 2004
Super Slurper	.025,.05,.1,.2,.4 % dw	S lm, cl lm, lm s			.2-160% inc, .4-300%inc	Hemyari, 1981
Hydromull (ureaformaldehyde)	200m3/ha	s lm, cl			200% inc (4.3 vs 9.7%)	Nimah et al., 1983
Agrisil (amorphous Na-silicate)	2 t/ha	s lm, cl			150% inc (4.3 vs 6.4 %)	Nimah et al., 1984
Mineral conditioners						
Zeolite	10 and 20 % v/v	Fine, med., cs sand	2 % in cs. Sand	1.50%	less than 1% in cs.sand	Bigelow et al., 2004
Vitrified clay	10 and 20 % v/v	Fine, med., cs sand	2 % in cs. Sand	1.50%	less than 1% in cs.sand	Bigelow et al., 2005
Diatomaceous earth	10 and 20 % v/v	Fine, med., cs sand	3.5 % in cs. Sand	3%	less than 1% in cs.sand	Bigelow et al., 2006
Calicined clay	10 and 20 % v/v	Fine, med., cs sand	3.5 % in cs. Sand	3%	less than 1% in cs.sand	Bigelow et al., 2007
Ceramic	10 % v/v	sand and peat	no inc in WC at -0.004 MPa			Li et al., 2000
Porous ceramic clay	10 % v/v	sand and peat	inc. by 2-4% g/g at -0.004 MPa			Li et al., 2001
Calcined diatomaceous earth	10 % v/v	sand and peat	inc. by 2-4% g/g at -0.004 MPa			Li et al., 2002
polymer coated clay	10 % v/v	sand and peat	no inc in WC at -0.004 MPa			Li et al., 2003
Fritted clay	100%	no soil	~33 % VWC at FC	~13 % VWC	20 % VWC	Van Bavel et al., 1978
Calcined clay	15 % v/v	quartz sand	Inc. VWC by 4% at -0.005 MPa			Waltz et al., 2003
Diatomaceous earth	15 % v/v	quartz sand	Inc. VWC by 4% at -0.005 MPa			Waltz et al., 2004

Appendix Section D. Literature Review of Evapo-Transpiration Model Parameters for Wild-Land Plants

Synopsis

In order to project results observed at the central California site to other areas around the state that differ in evaporation potential and plant type, a model of plant water-use is needed. This section reviews existing information on plant water-use models that may be adapted for use with wildlands plants and non-irrigated conditions.

Background

In agricultural systems, the Penman-Monteith model is used as the standard method to estimate crop evapo-transpiration. A brief introduction of this model and its intended use in this project are presented here. Although this model was not developed for roadside or wild-land vegetation, it is highly adaptable because it is mechanistic and its parameters can be modified to describe non-agricultural vegetation in different climatic regimes. The model was developed for well-watered, green, mowed grass (100 % coverage) growing on a large flat field (more information on the calculation of ETo is available at http://www.fao.org/docrep/X0490E/x0490e06.htm#TopOfPage). The water use of this mowed grass is used as a reference (or standardized) evapotranspiration value (ETo). The water use (EvapoTranspiration) of other crops (ETc) are then measured and compared to this reference value. The ratio of these two values is called the crop coefficient (Kc). It can be greater than 1.0 if the crop uses more than the reference mowed grass does, or, more often for wildlands plants, it is less than one.

Kc = ETc / ETo

The Kc of each crop must be determined. In California, an extensive network of ETo stations (California Irrigation Management and Information

System; CIMIS) have been set up so that farmers can access reference water demand (ETo) data. Then, by using published Kc values, they can determine how much water was used by their crops and irrigate them accordingly.

If the conditions of the field crop differ from the reference crop then the Kc value can be modified to adjust for differences in % cover, slope, aspect and water stress. As the % cover decreases from 100 % the amount of bare soil that is exposed increases. This increases the amount of solar radiation reaching the soil which increases evaporation as well as the amount of radiation that is reflected from the soil back up to the plants. Depending on the water content of the soil, the amount of evaporation will vary.

Soil evaporation occurs in three different processes or stages (Idso et al., 1974). The first stage occurs when the soil is well watered and evaporation is only limited by available energy. At this stage, surface mulches that shade the ground are effective, no matter how thin they are. In the second stage, the soil begins to dry out and the evaporation rate decreases rapidly. At this stage, the mulch thickness becomes functional, but only to the extent that it reduces diffusion of water vapor out of the soil by a combination of mulch thickness and small pore volumes and pore connectivity. The third and final stage occurs when very little water evaporates because the movement of water up the soil profile is limited by the unsaturated hydraulic conductivity of the dry surface soil layer. At this stage, it is the texture and structure of the underlying soil or substrate that creates the limitation for upward flow of water by capillarity, or the downward progression of drying as desiccation cracks open. Along landscaped roadways a mulch layer is often applied that acts to reduce the amount of evaporation from the soil. In order to account for either less than 100 % vegetation cover (increased soil evaporation) or a decrease in soil evaporation because of a mulch layer, the Penman-Monteith model can be adjusted by lowering the Kc value. A similar adjustment to the Kc value can be made if the slope or aspect varies from the reference crop. For example, a north facing slope will receive less solar radiation than a south facing slope throughout the year and so evapo-transpiration will be less. These slope aspect changes can create up to 14 %

increases in potential evaporation north-facing to south-facing changes in slope angle in California summers, and up to 37 % at northern latitudes (Weeks and Wilson, 2006) or, by extrapolation, in California during the lower solar angles of winter.

The most significant development and modification to the model for wild-land use in this project was the water stress coefficient (Ks). This component was necessary to add since wild-land plants commonly operate under water stressed conditions during much of the summer season. The Ks coefficient functions to account for reduced water use by the plant and ranges from a coefficient (multiplier) of between 1.0 to 0. At 1.0 there is no stress (100 % of potential transpiration) and at 0 the plants have stopped transpiring. The Ks coefficient does not decrease below 1.0 until the soil becomes dry enough that the plant begins to reduce water use. This value is plant-specific and must be measured empirically. Plants usually reduce water use when some predictable fraction of the soil plant available water is left. As the soil dries out, the Ks value decreases, approaching asymptotically to 0. The equation for water use of a given crop that will undergo water stress is as follows:

ETa (actual) = ETo x Kc x Ks

Crop water use can be calculated in hourly to monthly time steps depending on the input data. A daily time step was chosen for this project. In practice, the daily water use values are calculated based on the previous equations. As the plants become water stressed, they will reduce their daily water use from the maximum amount by some factor (Ks = ETa / ETc). The following literature review guided our development of Ks values specific for California plant species and environmental conditions.

Literature review

1. Garcia-Navarro, M.C., R.Y. Evans, R.S. Monterrat. 2004. Estimation of relative water use among ornamental landscape species. Scientia Horticulturae 99: 163-174.

This was a horticultural study that examined water use from *Arctostaphylos densiflora* that were planted in small pots and the water loss on repeated weighing was considered water use. The Kc for *Arctostaphylos densiflora* in this study was 1.77. This is a very high Kc value but is typical of Kc values determined using potted plants. The total % cover of the plants was ~40 %. It is highly unlikely that the Kc determined this way would be relevant to an actual field measured Kc value.

2. Levitt D.G., J.R. Simpson, J.L. Tipton. 1995. Water use of two landscape tree species in Tuscon, AZ. J. Amer. Soc. Hort. Sci. 120(3): 409-416.

Although this study also used potted plants, they used a much more realistic experimental approach. 57 liter pots where placed in the ground on scales. They measured the water use of *Quercus virginiana* (oak) and *Prosopis alba* (mesquite). When both species had 100 % cover, the Kc values for the oak and mesquite were 1.4 and 1.6 respectively.

3. Pochop L. and Kerr G.L. 1987. Influence of surface vs. subsurface irrigation on consumptive use of mountain meadow vegetation. Wyoming Water Research Center. WWRC-87-07.

This study used lysimeters in mountain meadows to measure the water used by perennial vegetation (grasses mainly). Based on moisture depletion data and ETo data, the Kc of the improved pasture was 0.92 at 100 % cover.

4. Poole, D.K. and P.C. Miller. 1975. Water relations of selected species of chaparral and coastal sage communities. Ecology 56: 1118-1128.

Poole and Miller examined water use from two vegetation communities in San Diego County. In both places they examined water use on North and South facing slopes. On the South facing slope in chaparral the % cover was only 63 % and the plants became stressed when 59 % of the PAW was depleted. On the North facing slope in the chaparral, there was 100 % cover and the plants didn't become stressed until 78 % of the PAW was depleted. On the coastal area, there was no difference in % cover between the North and South facing slopes (90 %) and both aspects became water stressed at 54 % PAW depletion.

5. Rowe, P.B. and L.F. Reimann. 1961. Water use by brush, grass and grass-forb vegetation. Journal of Forestry. March pg 175-180.

An elaborate system was constructed at the San Dimas Expt. Field station. They measured water use by the chaparral (42 % cover) using moisture depletion over several years. Based on historical ETo data and the data presented in the paper, I estimated that the Kc of the chaparral was 0.42 and began to regulate its water use when 59 % of its PAW was depleted.

6. Saucedo, D., T.W. Sammis, G.A. Picchioni and J.G. Mexal. 2006. Wastewater application and water use of Larrea tridentata. Agricultural Water Management. 82: 343-353.

*Larrea tridentat*e (creosote bush) was grown in 19 l pots in the Chihuahuan desert. The Kc of the plants was 0.75 with 50 % cover. Based on the data in the paper, I estimate that the plants start regulating water use at 50 % PAW depletion. This paper uses a similar model to the LIMP model to predict water use and its regulation.

7. Schuch, U.K. and D.W. Burger. 1997. Water use and crop coefficients of woody ornamentals in containers. J. Amer. Soc. Hort. Sci. 122(5): 727-734.

This study was done at Davis by the Horticultural department. They planted twelve woody shrub species in small pots. They kept the plants well watered and measured moisture depletion based on weight loss. Again, the Kc values are fairly specific to the growing conditions since fetch, % cover and other standard variables in the field are different than the conditions found in this experiment. The Kc values were quite high (1.77-2) for *Ceanothus* 'Concha', *Heteromeles arbutifolia*, and *Arctostaphylos densiflora*. If a correlation between field measured Kc values and pot grown plant Kc values were determined then these values may have some sort of practical value beyond nursery work.

8. Steinwand, A.L., R.F. Harrington, D.P. Groeneveld. 2001. Transpiration coefficients for three great basin shrubs. Journal of arid environments. 49:555-567.

This study attempted to develop a method of determining Kc values in the field based on leaf area and transpiration (porometry). They ignored soil evaporation. Three shrubs were examined and Kc values were determined for each. *Atriplex lentiformis* (salt brush), *Chrysothamnus nauseosus* and *Sarcobatus vermiculatus* had Kc values of 0.36, 0.8 and 0.6 during the middle of the summer. This approach was a good attempt however some measure of soil evaporation should have been made. As a result, the Kc values are most likely too low.

9. Or, D., D.P. Groeneveld. 1994. Stochastic estimation of plant-available soil water under fluctuating water table depths. Journal of Hydrology. 163: 43-64.

This study was conducted in the Owens valley to measure water use of native vegetation. Leaf area index and porometry were used to develop Kc values for *Atriplex torreyi* (0.54), *Chrysothamnus nauseosus* (1.07), *Sarcobatus* *vermiculatus* (0.97), *Distichlis spicata* (0.75) and *Sporobolus airoidos* (0.7). The total cover of the native vegetation was 60 % so the Kc values do not represent a closed canopy. This is the best data set of Kc values but they most likely underestimate the true Kc values since soil evaporation was not taken into account.

10. Wight, J.R., R.J. Hanks. 1981. A water-balance, climate model for range herbage production. Journal of Range Management. 34: 307-311.

Using rough estimations of ETo and soil moisture depletion, this study determined that the Kc of an improved pasture was 0.85. The Kc ranged from 0.7-0.9 during the study period.

11. Mata-Gonzalez R., T. McLendon, D.W. Martin. 2005. The inappropriate use of crop transpiration (Kc) to estimate evaporation in arid ecosystems: a review. Arid Land Research and Management. 19: 285-295.

This review was a critique on using agricultural water use models in wildland areas. They reviewed many of the studies referenced above and detailed where they did not meet the assumptions of the ET model. The biggest problems they found were problems of scale and growth conditions. Porometry data often underestimate total plant transpiration. Wildland plants also typically display stomatal control that was not accounted for in the studies. Some of the studies did not measure water use under well watered conditions which violates the assumptions of the ETo model. For all their criticism however, they did not propose a practical alternative.

12. Zwieniecki, M.A., M. Newton. 1996. Seasonal pattern of water depletion from soil-rock profiles in a Mediterranean climate in southwestern Oregon. Can. J. For. Res. 26: 1346-1352.

This study looked at water use by three shrubs in a clear cut area. No Kc could be determined from the data but moisture depletion data showed that *Arctostaphylos viscida* begins to reduce its water use when 40 % of the PAW is depleted.

Conclusions

A range of crop coefficients (Kc) for wild-land plants were found in the literature. The studies that measured water use by loss of weight from a potted plant often presented Kc values that were quite large (>1.5). The growth conditions of these plants do not closely resemble the growing conditions of roadside vegetation and the use of model parameters developed from these experiments would not be advisable to be used for roadside vegetation. The pot study by Levitt et al. (1995) however, was most relevant because they used large pots buried in the ground with 100 % canopy cover. The Kc values they proposed for oak and mesquite can be considered good approximations. Pochop and Kerr (1987) was the only other study that provided what seems to be a reasonable Kc value (~0.9 for perennial pasture). The rest of the studies either did not have a closed canopy (>80 % cover) or did not take into account evaporation from the soil. For these reasons the proposed Kc values can only be applied to the specific situations they were developed from.

For the range of plant types found in these studies (mainly shrubs), the point at which the plants began to reduce water use ranged from 40-78 % of the PAW. This shows the range in ability by shrubs to regulate water use when water stresses. A conservative approach would be to reduce water use at when ~40 % of the soil's PAW is depleted (60 % of PAW remaining). This would improve the chances that soil water resources would sustain the plant through the dry season. On the other hand plants that live near wet areas such as riparian vegetation may not reduce water use until ~70 % of the soil's PAW is depleted.

A review of the literature concerning evapo-transpiration model parameters (Kc and Ks) for wildland plants shows that it is possible to determine these parameters but may be difficult to satisfy the assumptions of the model. Researchers hoping to use these models on wildlands plants should determine pertinent model parameters for the specific plant types they are interested in until a broader data base consisting of uniform methodology exists.

Table 1. Crop coefficeint data and water stress points reported in the literature: Compiled data from Appendix B

Plant Species	Kc	% PAW	%ETo	% cover	Location	Reference	notes
Baccharis pilularis (coyote bush)	0.96	60	20	50	Davis, CA, Riverside, CA	Curtis (unpublished), Pittenger et al. 2001	surfance renewal, trials
Arctostaphylos densiflora	1.77	n/m		40??	Davis, CA	Garcia-Navarro et al. 2004	container study
Prosopis alba (mesquite)	1.6	n/m		100		Levitt et al. 1995	container study
Quercus virginiana (oak)	1.4	n/m		100		Levitt et al. 1995	container study
Improved pasture (perenial veg)	0.92			100	Laramie, Wyoming	Pochop and Burman, 1986	Lysimeters
Chaparrel (Adenostaoma, Arctostaphylos, Ceanothus, Rhus and Salvia apiana)		59		63	San Diego, CA	Poole and Miller, 1975	moisture depletion, South facing slope
Chaparral (Heteromeles, Ceanothus, Adenostoma, and Arctostaphylsu)		78		100	San Diego, CA	Poole and Miller, 1975	moisture depletion, North facing slope
Coastal sage (Artemisia californica, Rhus laurina, Rhus integrifolia, Heteromeles)		54		90	Camp Pendleton, CA	Poole and Miller, 1975	moisture depletion
Chaparral (scrub oak-61%, mountain mahogany-27%, hoaryleaf ceanothus-10%	0.42	59		42	San Diego, CA	Rowe and Reimann, 1961	lysimeter
Larrea Tridentata (creasote bush)	0.75	50 (est.)		50	Las Cruces, NM	Saucedo et al. 2005	container study
Arctostaphylos densiflora	2.00	n/m		100	Davis, CA, Riverside, CA	Schuch and Burger, 1997	container study
Ceanothus 'Concha'	1.7	n/m		100	Davis, CA, Riverside, CA	Schuch and Burger, 1997	container study
Heteromeles arbutifolia	1.7	n/m		100	Davis, CA, Riverside, CA	Schuch and Burger, 1997	container study
Atriplex lentiformis	0.36			35		Steinwand et al. 2001	agroclimatology
Chrysothamnus nauseosus	0.8			20		Steinwand et al. 2001	agroclimatology
Sarcobatus vermiculatus	0.6			15		Steinwand et al. 2001	agroclimatology
Atriplex torreyi	0.54			19 (60)	Owens Valley, CA	Or and Groeneveld, 1994	LAI, porometry
Chrysothamnus nauseosus	1.07			8 (60)	Owens Valley, CA	Or and Groeneveld, 1994	LAI, porometry
Sarcobatus vermiculatus	0.97			10 (60)	Owens Valley, CA	Or and Groeneveld, 1994	LAI, porometry
Distichlis spicata	0.75			17 (60)	Owens Valley, CA	Or and Groeneveld, 1994	LAI, porometry
Sporobolus airoides	0.7			6 (60)	Owens Valley, CA	Or and Groeneveld, 1994	LAI, porometry
Improved pasture (perenial veg)	0.85			100	Montana, North Dakota	Wight and Hanks, 1981	LAI, soil moisture depletion
Arctostaphylos viscida (whiteleaf manzanita)		40		100	Applegate, OR	Zwieniecki and Newton, 1996	moisture depletion

References

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Appendix Section E. Exploratory Experiment to Develop Crop and Stress Coefficients for Coyote Bush:

Section synopsis

Plant water use can be estimated by multiplying potential evaporation times a plant canopy factor times a stress factor for when plants reduce water use. These values are well known for crop species but not for wildlands plants common for mitigation projects. This section summarizes work done to identify these values.

Introduction

Values for crop coefficients (Kc) and stress coefficients (Ks) of common Californian wild-land plants are not known and need to be experimentally determined. An exploratory experiment was conducted that was designed to minimize costs while accomplishing end goals. Traditional assumptions of the Pennman-Monteith equations state that model parameters should be developed for monocultures with a closed canopy. Since micro-meteorology (micro-met) is used, adequate fetch (upwind space of undisturbed homogeneous plant canopy) must be satisfied. Generally this means that for every meter above the ground the instruments are located there needs to be 50 meters of upwind fetch. Most micro-met stations are located at 2 meters above the ground, so this implies that there needs to be 100 meters of undisturbed vegetation in all directions of the station.

Planning this experiment required the balancing of practical limitations with the need for an experiment that yielded realistic results. This project focused on the measurement of a Kc value for our plant type and then monthly Ks values during the summer months. First of all we identified a location were we could measure the Kc parameter. A micro-met station which is part of the California Irrigation Management Information System (CIMIS, measures ETo) is located on the University of California, Davis campus (Cambell tract). The Kc parameter is the result of the ETa/ETo so it was important that we had accurate

ETo measurements. We determined that coyote bush was an appropriate plant type that has a broad distribution along California's roadsides. The ETa of coyote bush located adjacent to the CIMIS station would provide the information needed to calculate this plant's Kc.

A monthly time step was determined to be sufficient to calculate Ks values since daily values could be interpolated from these values later. Research plots were constructed at Contra Costa highway 4 that would provide both well-watered and water stressed plants. It is the ratio of water-stressed water use to well-watered water use that determines the Ks parameters. Research plots were also monitored for soil moisture so that the point at which the plants begin to regulate water use could be determined.

The determined Kc value was then incorporated into a daily water use model (based on the Pennman-Monteith equation). The model was modified to account for soil water resources, where daily water use was subtracted from the remaining resources. Based on soil moisture data, we predicted when the plants would start regulating their water use and then compared that to the Ks values that we measured.

Methods

A 10 x 10 m area adjacent to, but downwind from the CIMIS station located on the UC Davis Campbell Tract was planted with coyote bush (0.75 m on center). These plants were planted in March 2006. A fence was placed around the plot to keep rabbits from eating the young shrubs (Figure 1). This plot does not meet the fetch criteria mentioned earlier but the turfgrass conditions located upwind of the plots were estimated to reduce the error associated with this condition, reducing the over estimation that would occur with bare soil.

Figure 1. Coyote bush containers immediately after planting that will be used to measure crop and stress coefficients for this wildlands species after they are established. Photo taken into the direction of prevailing winds during measured evaporation periods, showing turfgrass fetch.

Only data from days where the prevailing wind came from the south were used in calculations. Plants were irrigated approximately every ten days when the turf was also irrigated. Sprinklers located in the turf were adjusted to also water the coyote bush plot. Irrigation events lasted 12 hours and were assumed to saturate the soil profile. In this way all the coyote bush plants were kept in a well watered condition.

The surface renewal technique was used (instruments shown in Figure 1 above) to estimate ETa. This method costs only a fraction of the amount that the more traditional eddy covariance method would cost. It is also well suited to small areas such as the coyote bush plot used in this study. Its sensors are located one meter above the soil surface further reducing the need for a long fetch. This surface renewal station was calibrated as prescribed by Richard Snyder (UC Davis, Atmospheric Science extension specialist). Each month, plant cover was measured starting in June. Twenty plants were measured for canopy area, where five plants in each quadrant were randomly selected and their widths (longest and perpendicular length) looking from the top were measured and the area was calculated as that of an oval. The Kc of the coyote bush was calculated every month. Data from the surface renewal station was collected and converted to ETa. Data from the adjacent CIMIS station was used to calculate ETo.

Research plots at Contra Costa highway 4 were constructed that were located adjacent to the previous research plots mentioned in Section 7. Six 2 x 2 m (6 x 6 feet) plots were constructed, alternating in tillage depth from 0.5 m (18”) and 2 m (6 feet) so that there were three shallow plots and 3 deep plots. Coyote bush were planted at 0.75 m (30”) on center, with four shrubs per plot (Figure 2).

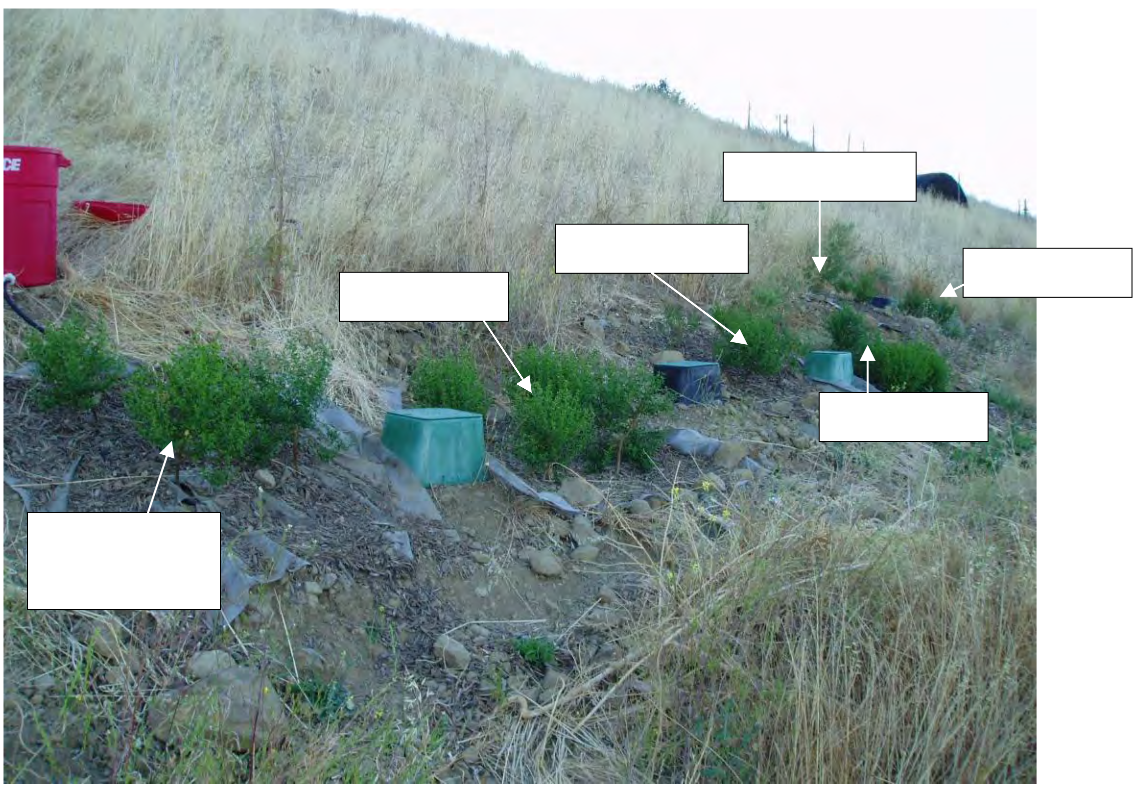


Figure 2. Experimental plots to determine crop and stress coefficients at Contra Costa highway 4.

The 0.5 m (18”) deep plots were lined with plastic so that the exact amount of plant available water (PAW) in the plot could be controlled. Moisture probes (TDT) were placed in the 0.5 m (18”) deep plots at 20 and 40 cm (8 and 16”). In the 2 m (6 foot) deep plots, moisture probes were placed at 20, 40, 80, 120 and 190 cm (8, 16, 32, 64 and 75”). Moisture readings were taken every 6 hours. One of the 0.5 m (18”) deep plots was used as the well watered plot to estimate water use under sufficient moisture conditions. The plot was irrigated monthly using a passive irrigation system (soaker hoses connected to a large bucket located above the plot) where 130 liters of water was delivered uniformly to the plot over ~12 hour period.

Water use from the coyote bushes in the plots was determined by measuring sap flow in each plant. The Sap Flow System is made by Dynamax Company. Sensors are placed around the stem of the plant and a heat pulse is applied at the center of the sensor thereby heating up the sap in the stem. There are small thermocouples located at the edge of the sensor which measured the change in temperature of the sap flowing up the stem. A large change in temperature measured by the upper thermocouple indicates greater sap flow up the stem. The heat loss inherent in the stem was calculated by measuring temperature fluxes during the night when the bush was bagged to insure there was no transpiration occurring (as prescribed by the user’s manual). Sap flow measurements were done on the well watered (four plants) and water stressed plants (four plants) during the first week of each month (July, August, September and October). Four days were required to measure sap flow: day 1-sensors were installed on plant stems at midday and values were checked at night to make sure readings were being taken, day 2 and 3-sensors were allowed to collect data and plants were bagged at evening on the 3rd day, day 4-probes were removed from plants. On day 4, plant measurements were also taken. These included plant height, leaf area index (LAI) and percent cover. Leaf area index was measured by counting the number of leaves in one quarter of the shrub. Leaf area was measured on one branch. Length and width of the leaves were measured and the area was calculated by assuming an oval shape. Percent cover was calculated as previously described.

Water use was calculated for the well-watered and water-stressed plots on the bases of mL of water transpired per square cm of leaf area. This was done to normalize water use measurements since the well-watered plants would soon grow much bigger than the water-stressed plants and a total measurement of water use would result in erroneously low Ks values. Sap flow gave the total amount of water used during a day in mL and the LAI data was used to calculate total leaf area. Total water use divided by total leaf area gives mL/cm^2.

It must be noted that when sap flow measurements were to be taken in September we found that the shrubs on the well watered plots were dead. Their roots had been girdled and eaten by rodents (Figure 3). The well watered conditions evidently provided good habitat for these animals.

Figure 3. Rodent damage to shrub roots

As an alternative to using monthly sap flow from the well watered plot, we devised an alternate method of estimating water use from a well-watered plot. Good data was collected from the month of June for the well-watered plants. The daily average ETo for the month of June was used as a normalizing value and the average daily ETo values of the following months were divided by this factor. For example, the average daily ETo in June was 6.2 mm and for July it was 5.5 mm. July's value divided by June's value equals 0.88. This value was then multiplied times the water use value for June in order to estimate the water use for July. This was done for all subsequent months in order to estimate water use from a well-watered plot.

A CIMIS weather station is located ~15 km from the research site. A standard ETo micro-met station (Campbell Scientific, ET107 ETo monitoring station) was installed at the Contra Costa highway 4 site. We compared the ETo values from this location to the CIMIS location. Measurements were taken from August 1, 2006 to January 11, 2007. The influence of slope, aspect and vegetative cover (non-ideal) were expected to cause the ETo measurements at the research site to differ from the CIMIS station (ideal conditions). Hourly values were used to calculate daily water use from the research site. The micro-met station was placed in a relatively flat location (Figure 4).

Figure 4. Evaporation measurement station at Contra Costa highway 4.

Once Kc and Ks values were determined, local climate data from the nearby CIMIS station was input into an evapo-transpiration model named Landscape Irrigation Management Program (LIMP). This model was developed by Richard Snyder and is based on the Penmann-Montheith model. It takes into account weather data, crop type, % cover, slope, aspect and was modified to also include available soil water resources to control the Ks coefficient. A much more detailed explanation of the model can be found at:

http://biomet.ucdavis.edu/irrigation_scheduling/LIMP/limp.pdf

Soil water resources were calculated in the plots and input into the model. The LIMP model uses a mathematical equation to predict how Ks changes over time once Ks < 1. Measured Ks values were then compared to predicted Ks values from the LIMP model. Two types of measured Ks values were used for comparison. The Ks values developed from the sap flow data were used as discussed previously, as well as an estimate of Ks comparing daily moisture depletion in the irrigated plot and the 2 m (6 foot) deep plot.

Results and Discussion

Kc values measured at Campbell Tract:

As the coyote bush became larger over the year their water use also increased as seen by the larger Kc values over time (Table 1). Measurements were not taken during the winter because evapo-transpiration rates are very low. Crop coefficient values near 1 indicate that when the percent plant cover was 20-40 % the water use was similar to that of turf grass. When the canopy cover was nearly complete (81.4 %) ETc from the coyote bush plot was over one third greater than that of turf grass (1.36 vs 1, Figure 5).

Figure 5. Mature stand of coyote bush used for crop and stress coefficients. View from the direction of wind flow across the mowed grass.

The Kc value would not be expected to increase above 1.36 since ETc from crops with 80-100 % plant cover are assumed to be equal (Richard Snyder, UC Davis, personal communication). Coyote bush is opportunistic in its growth pattern. In well watered conditions it is quite reasonable that its water use would exceed that of turf grass. Levitt et al. (1995) found similar Kc for oak and mesquite trees (1.4 and 1.6) in their study. For these reasons, we feel that our estimate of the crop coefficient of coyote bush is a reasonable approximation.

There are two possible sources of error associated with the Kc value we measured. First of all, the size of the plot was smaller than ideal. The plot was located adjacent to a well watered turf grass plot on the south but in all other directions was clean tilled farmland. Although data was screened for wind direction, some amount of less than ideal wind direction was allowed. This would result in an underestimation of ETc when the surrounding soil became dry. Also, when the water use of the coyote bush began to exceed the water use of the turf grass (~40 % cover), the influence of the turf grass would cause an underestimation of ETc. In light of these possible errors, the Kc value of 1.36 could be an underestimation of the actual Kc value.

The second possible source of error could be the method we chose to use to evaluate ETc. Surface renewal is a newer method that has not been extensively tested for many applications. It is very dependent on calibration and continued maintenance of the measuring instruments. For example, it uses fine wire thermocouples to continuously measure heat ramps in the air above the plants. These probes seemed to attract spiders that made their webs among the thermocouples. Even the slight pull of a spider spinning its web sometimes resulted in the thermocouple wire breaking. Every method has its drawbacks but the influences of these drawbacks for the surface renewal method are not well documented at this point. Future use of this Kc value must be done with the full knowledge of the caveats associated with it.

Table 1. Percent cover and coefficient (Kc) of coyote at the Cambell Tract, UC

Date	%	Kc
6/15/200	3.3	0.79
7/15/200	8.6	0.78
8/15/200	20.3	0.99
9/15/200	36.0	1.04
10/15/200	40.3	1.06
3/14/200	81.4	1.36

Evaluation of water stress in coyote bush at highway 4 site:

Coyote bush had already begun reducing water use by June (Table 2). During the year of the study (2006), average daily ETo values were greatest for the month of June in at this location. Stress coefficients dropped to ~0.1 by August and remained there for the remainder of the season. It is important to note that the plants growing on the water-stressed plots were very near death by the end of October (Figure 6).

Figure 6. Well watered and water stressed plants at Contra Costa highway 4.

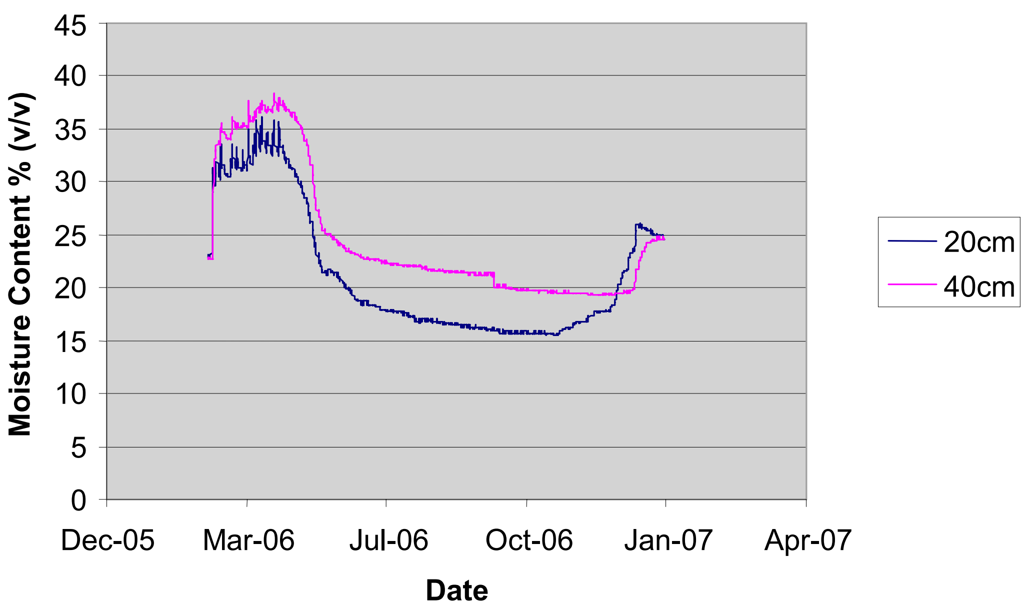
The 2 m deep plot on the left shows the dramatic difference in plant growth when adequate soil moisture is provided. Sap flow measurements were only taken on plants that still had green leaf tissue as some had become completely brown.

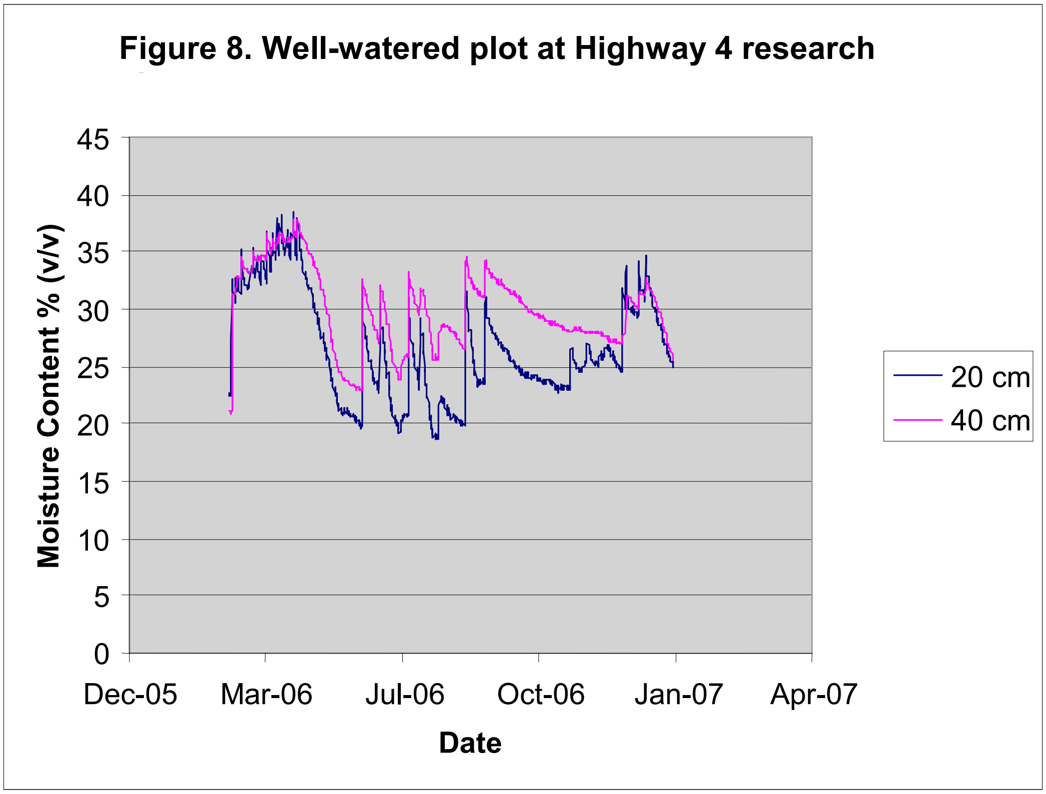
Table 2. Crop stress coefficients (Ks) for coyote bush grown at Highway 4 study site.

	ETo ratios	Well-Watered mL/cm^2	Water-Stressed mL/cm^2	Ks
June	1.00	0.95	0.35	0.37
July	0.88	0.84	0.19	0.23
Aug	0.92	0.87	0.10	0.11
Sept	0.75	0.71	0.11	0.16
Oct	0.50	0.48	0.06	0.14

Soil moisture data also confirm that plants began to reduce water use by mid May (Figure 7). Plants in the irrigated plot only briefly reduced water use in late May but quickly recovered once irrigation began (Figure 8). The moisture content in the water-stressed plots at 20 cm had a maximum post drainage content of ~33 %. The coyote bush began to reduce water use when the moisture content was ~22 % and the minimum water content at the end of the summer was ~15 %. This indicates that there was ~18 % PAW in the soil. This is an operational estimate of PAW since we do not know the matric potentials at these moisture contents. When 11 % (33-22 %) of the water was depleted, the plants began to reduce water use. This indicates that when ~60 % (11/18 = 0.61) of the PAW in the soil is removed, that coyote bush will begin to reduce its water use. This behavior can be used to understand how plants use or conserve moisture according to their perceived soil water conditions.

Figure 7. Water-stressed plots at Highway 4 research site

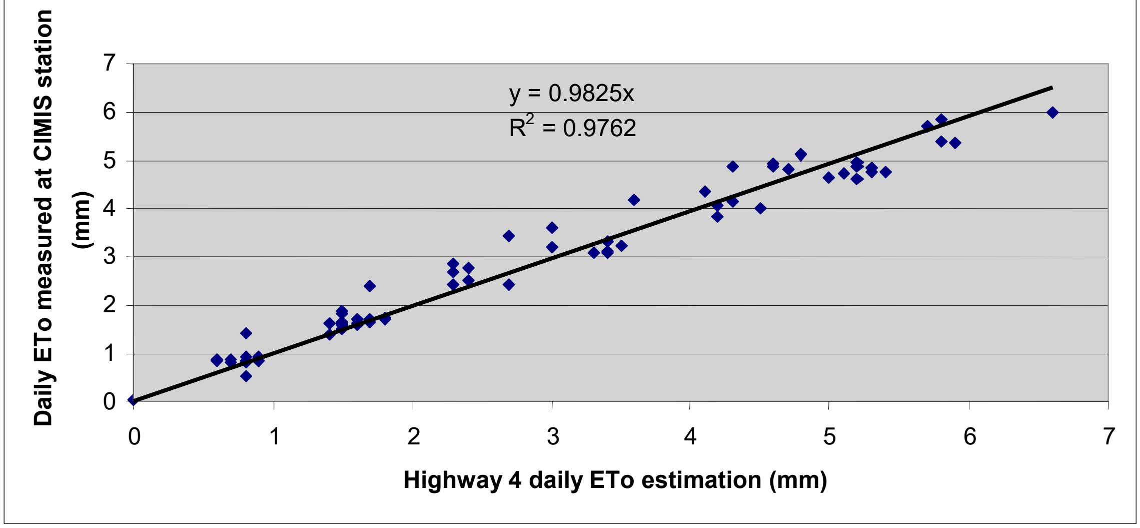




Micro-met station ETo estimate at research site:

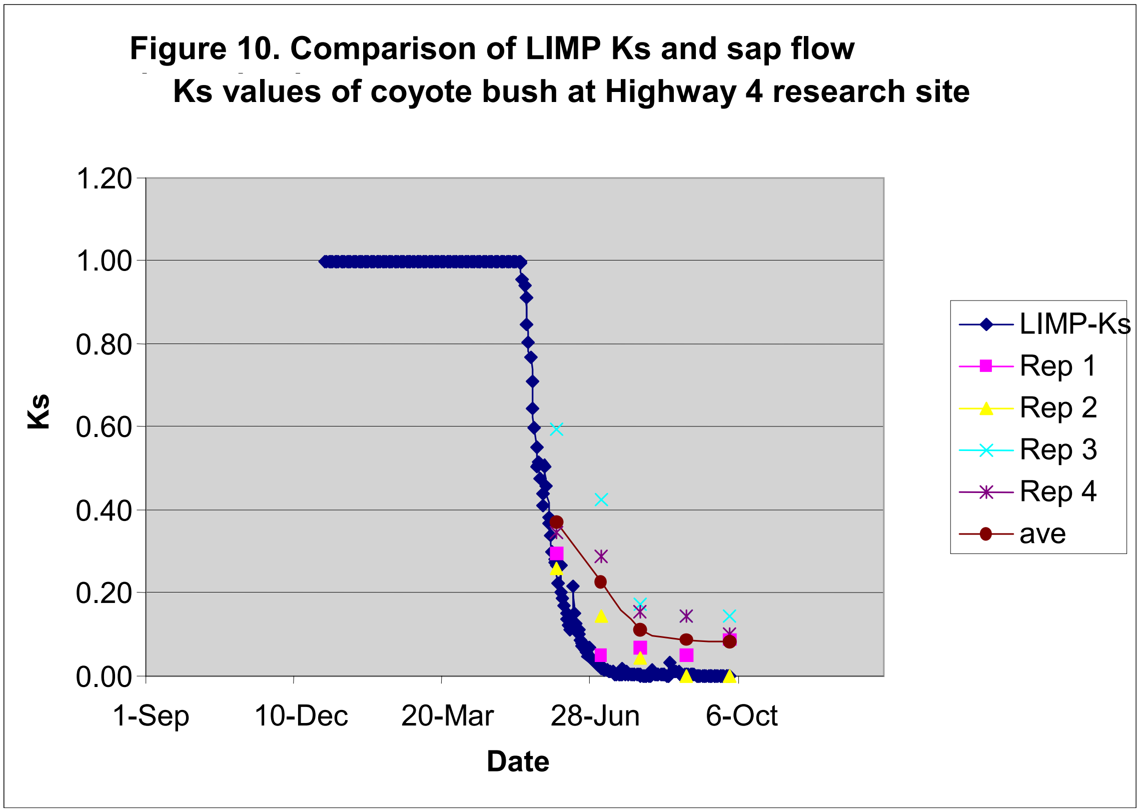
Despite the fact that the ETo measurements taken at the Highway 4 research site were done under less than ideal conditions, they compared very well with ETo measurements from the nearby CIMIS station (Figure 9). This indicates that CIMIS data can be used to estimate ETo values for nearby roadsides. This has implications for future modeling work that could utilize the long term data that is available from this network.

Figure 9. Comparison of ETo estimate at Highway 4 research site with local CIMIS station



LIMP model comparison with field observations:

Monthly average ETo and daily precipitation values from 2006 were input into the LIMP model as measured by CIMIS station #170. The soil water resources of the plots were also input into the model (PAW and plot depth). An estimate of monthly plant cover during the growing season was also input. The Kc determined from the Campbell Tract plot was used for coyote bush (1.36) in the model as was the point at which the Ks becomes lower than 1 (60 % of PAW as determined on Highway 4 plots). Figure 10 shows the predicted decrease in Ks from the LIMP model as compared to the Ks values experimentally determined using sap flow. The point at which Ks began in the LIMP model appears to match the observed data. Earlier sap flow measurements should have been taken before water stress occurred however, the sap flow equipment was available and calibrated until the first of June. The predicted Ks from the LIMP model declines steeply whereas the measured Ks appeared to have a more gradual decline.



When the moisture probe data was used to determine water use in the well-watered 0.5 m (18”) and 2 m (6 foot) deep plots, the resulting Ks values did not agree with the LIMP predicted Ks values (Figure 11). The shape of the Ks curve is similar between methods but the time where Ks dropped below 1 differs by ~one month (Figure 12). The soil moisture data shows that the plants began to reduce water use around mid May. This is also in agreement with the sap flow results. The LIMP model assumed that there was 2 m (6 feet) of soil accessible for plant extraction of water. But, since this was the first year of plant growth, the roots of the coyote bush may not have extended to 2 m (6 feet). Evidence of this can be seen in Figure 6 where 2 m (6 feet) moisture measurements decrease under drainage until the first of July. After the first part of July the soil moisture decreased rapidly presumably because of plant extraction. When the LIMP model input for soil depth is changed from 2 m (6 feet) to 1 m (3 feet) to account for probable root depth during the early part of the year, the predicted Ks values closely match the measured Ks values (Figure 13). Plants growing in deep soils may extract water differently than ones growing in shallow soils. Data collected in subsequent years, after the roots were already established in the whole soil profile, would answer this question.

Figure 11. Comparison of LIMP Ks and moisture probe values of coyote bush at Highway 4 research site (2 m

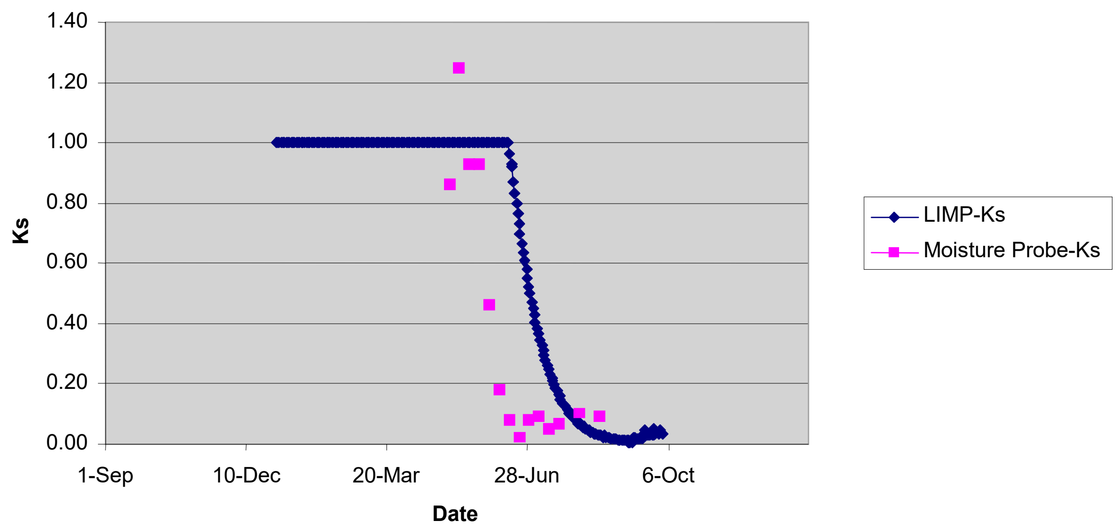
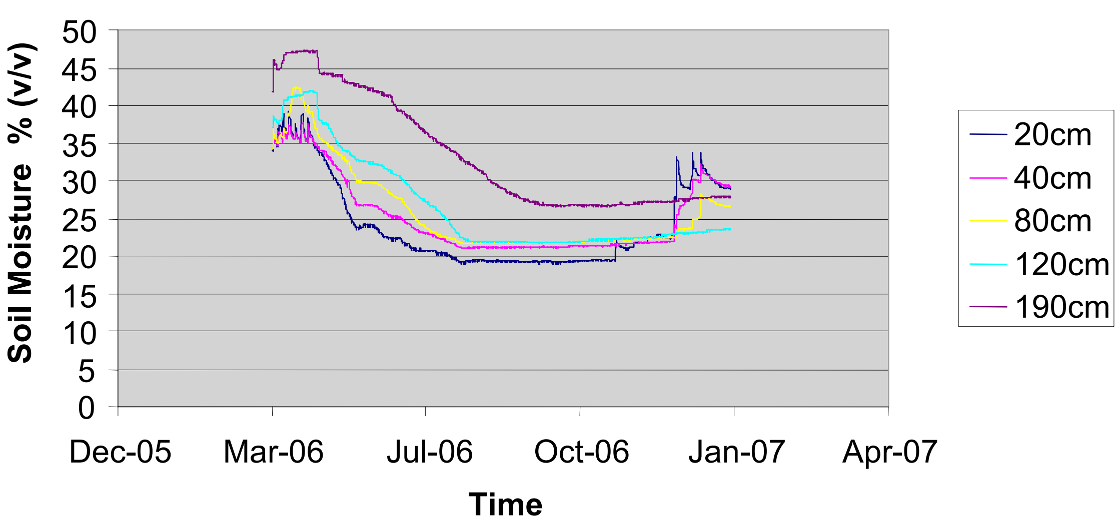
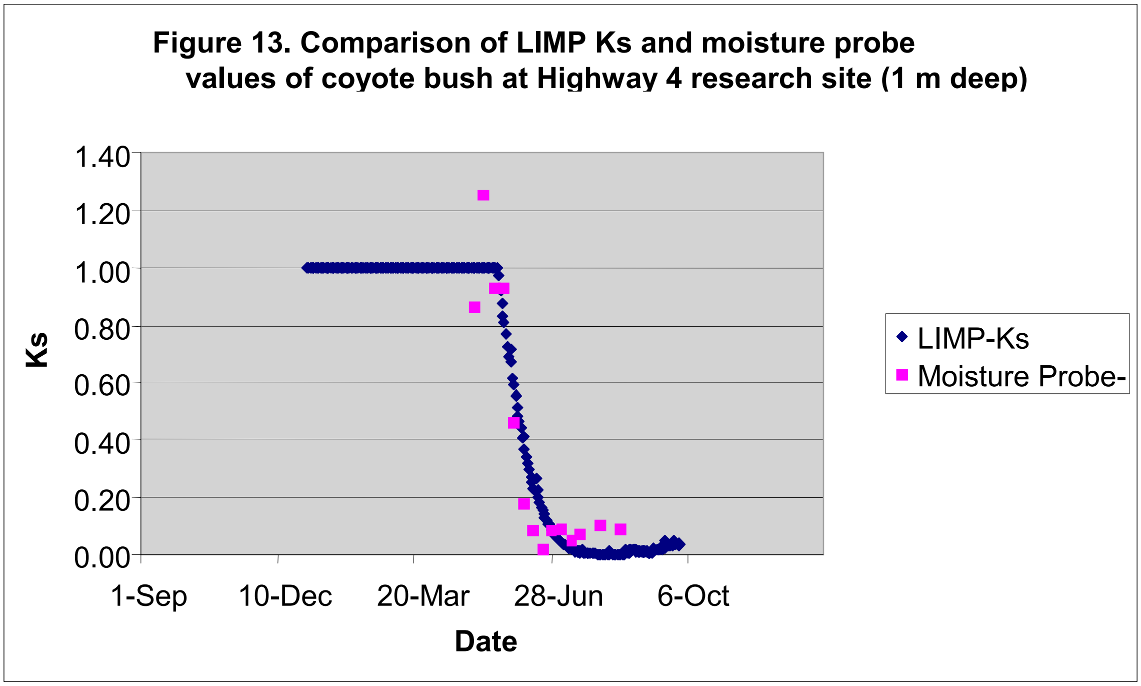


Figure 12. Moisture content under coyote bush 2m deep plots a Highway 4 research site





Conclusions

An approximation of the Kc of coyote bush was determined using the surface renewal method and found to be 1.36. Establishing dense stands of various shrub species that would be of interest to revegetation planners would be impractical. But, if naturally occurring monocultures that satisfy the model assumptions could be found, then additional Kc values could be determined from these naturally occurring stands. Surface renewal was a simple and cheap method of measuring ETa but future measurements should be confirmed with standard methods as well.

Soil moisture measurements provided a good method for determining the % of PAW where stress begins and the stress coefficient (Ks) goes below 1.0. Coyote bush began reducing its water use when 60 % of its PAW was used. Sap flow measurements provided accurate Ks values over time, but creating field plots that satisfy well-watered criteria was difficult.

Local micro-met data collected at Highway 4 was very similar to data collected by the local CIMIS station. This suggests that long term CIMIS data from stations located around the state may be used to estimate the ETo along roadsides. Distance from CIMIS station as well as elevation needs to be factored in, but for our purposes in most situations these stations will provide acceptable data.

The LIMP model reasonably correlated well with measured water use from coyote bush growing at the Highway 4 research site. Future use of this model for estimating water use needs roadside vegetation seems very practical. Weather data from the CIMIS network around the state can be used for monthly ETo and precipitation. For each plant type of interest a data base of Kc and Ks (% of PAW where Ks begins) values can be used along with an estimate of plant cover and soil depth to determine if there are enough available water resources for sustained plant growth. Based on this model, future research needs to be done to develop a planning tool for roadside revegetation projects that will specify the needed soil water resources at a specific location to grow a particular plant at a required plant density.

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Appendix Section F. Measurement of Crop Coefficients of Three Wild-Land Shrubs

Synopsis

This section describes work to get modeling parameter data for three shrubs using existing wild-land stands to avoid having to make a uniform garden plot of these different species.

Introduction

The accuracy of water use models are dependent on the quality of the data that the parameters used in the model are derived from. There is a wealth of information on crop water use model parameters for agricultural crops. However, as reported in section 8 of this report, there has been very little published about wild-land vegetation. The most important plant parameter that is needed for water use models is the crop coefficient (Kc). This parameter is most easily measured in a large flat field consisting of a monoculture that covers over 80% of the ground surface under well watered conditions. In wild-land situations all of these conditions are seldom satisfied at one time. It was our challenge to find three locations that most closely satisfy these conditions that were each occupied by one of the three wild-land species of interest in this project. Since Kc values are the ratio of the measured evapo-transpiration of the crop of interest (ETc) and the standard reference crop (ETo), there also needed to be a nearby location that measured ETo. Data from California Irrigation Management Information System (CIMIS) sites was used to calculate ETo.

Three shrubs were identified as having a broad distribution and application in roadside planting projects: coyote bush, manzanita and (Basin) sage brush. These shrubs also represent distinct climatic regions in California, where water use decreases as follows coyote bush>manzanita>sage brush. Coyote bush is found in the coastal mountains and much of the central valley. Manzanita is in dryer areas including the foothills of the Sierras. Sage brush is widely distributed along the eastern part of the Sierras and the Great Basin. These plants represent the range of water use in California's diverse climate regions.

Coyote bush (*Baccharis pilularis*):

This shrub is widely distributed in the central valley and coastal mountains however much of the flat areas have been cleared for housing or farm land. A survey of the coastal mountains showed that there was a large stand of coyote bush at Nicasio Reservoir in Marin County (Figure 1). It is not located on flat land but the slope is uniform and the dominant wind direction blows across the face of the slope, providing 100 m of uniform fetch. The dense vegetation cover was also estimated to be over 80% of the soil surface. CIMIS station #187 (Black Point) was the station used for ETo values.

Figure 1. View of coyote bush at Lake Nicasio. This is the direction from which the prevailing winds come.

Manzanita (*Arctostaphylos patula*):

Manzanita is a drought tolerant shrub found throughout the dryer foothills and mountains of California. It quickly invades disturbed areas and can quickly form a dense monoculture. A large undeveloped section of land near the Redding airport was identified that consisted of such a monoculture (Figure 2). The plants were not very old (~10 years) but formed a dense stand of ~100% surface cover. CIMIS station #8 (Gerber) was used for ETo values.

Figure 2. View of manzanita shrub at near the Redding Airport. This is the direction from which the prevailing winds come.

Sage brush (*Artemesia tridentata*):

In California's most arid environments such as in the great basin, sage brush dominates much of the landscape. Its physiology is well suited for the harsh environmental conditions found in these areas. It is slow growing and can regulate its water use very efficiently. Since sage brush lives in very dry places it is no surprise that it does not grow in dense stands. An extensive survey trip in the great basin area and using Google Earth software was conducted to find an area with a greater than 70% cover, however no such area was found. A maximum of ~35% cover was found. A suitable location near Alturas California was found (Figure 3). CIMIS station #90 (Alturas) was used for ETo values.

Figure 3. View of sagebrush stand near Alturas, CA.

Methods used to measure ETa at each location:

Two methods were used to estimate/measure evapo-transpiration (ETc) from wild-land plants. Surface renewal was used to estimate ETc as proposed by Consoli et al. (2006). This is a newer method used to estimate crop water use and has not yet been broadly accepted. It is much cheaper than other traditional methods, and if proved sufficiently accurate for measuring the ETc of wild-lands plants, then future projects could use this method and save considerable amounts of money. This would be especially useful if wildlands managers wanted to be able to plan for several additional plant types that differed from the three shrubs selected here, including perennial grasses and forbs. For reasons of economy, this more inexpensive method was used alongside the eddy covariance method to evaluate the appropriateness of its use in wild-land environments.

The eddy covariance technique was used to measure ETc directly at each of the sites (Stull 1988). This is a standard method that measures the vertical wind speed and the absolute humidity over the plant canopy (Baker and Norman, 2002). A 3-dementional sonic anemometer was used to measure vertical wind speed and the absolute humidity was measured using an infrared gas analyzer.

These instruments were placed at each location for approximately two weeks during the spring when soil water was assumed to not be limiting. Soil moisture probes were placed in the soil at 20 and 40 cm at each location to evaluate if this assumption was, in fact, correct. Measurements needed to be taken during well watered conditions in order to calculate the crop coefficient as described in previous sections. Monitoring instruments were placed at the manzanita site on April 18 and removed on May 9. They were placed at the coyote bush site on May 11 and removed on June 1. The sage brush site was monitored from June 4 through the 19. Data was screened for wind direction. Daily data for which two thirds of the hourly measurements were from a wind direction that did not have adequate fetch were discarded.

Results and Discussion

A summary of the data collected for the three plant types is presented in Table 1. Although ETc from the manzanita was measured earlier in the spring than the other plants its ETc was the largest. Reference ETo as measured at the CIMIS stations was similar for all locations. Water use (ETc) by coyote bush appeared to be on a slight downward trend over the study period (Figure 4). By the end of the study period, the ETc values were some of the lowest measured.

Table 1. Crop coefficients measured for coyote bush, manzanita and sage brush

Plant Type	Ave. ETc (mm)	Ave. ETo (mm)	Kc	SD*
Coyote Bush	1.7	4.6	0.38	0.07
Manzanita	3.5	4.6	0.71	0.14
Sage Brush	0.7	5.0	0.13	0.06

*SD-standard deviation

An error occurred during the downloading of soil moisture data at the coyote bush site for the time of the study period and all the data was lost. It cannot be stated what the soil moisture status was during the time of the study period. Soil moisture for the year following the study period is presented in Figure 5 and we can see that plant water use begins to become reduced by early May. This was also the case in a previous study at Highway 4 where plants began reducing water use around mid May. The beginning point of water stress will be different for every location depending on available soil water resources and local climate factors. The fact that the Kc value of coyote bush was calculated to be 0.38 indicates that the study was done under water limiting conditions. Our previous measurement of the Kc of coyote bush was 1.36. Measurements should have been taken earlier in the growing season when soil moisture was not limiting.

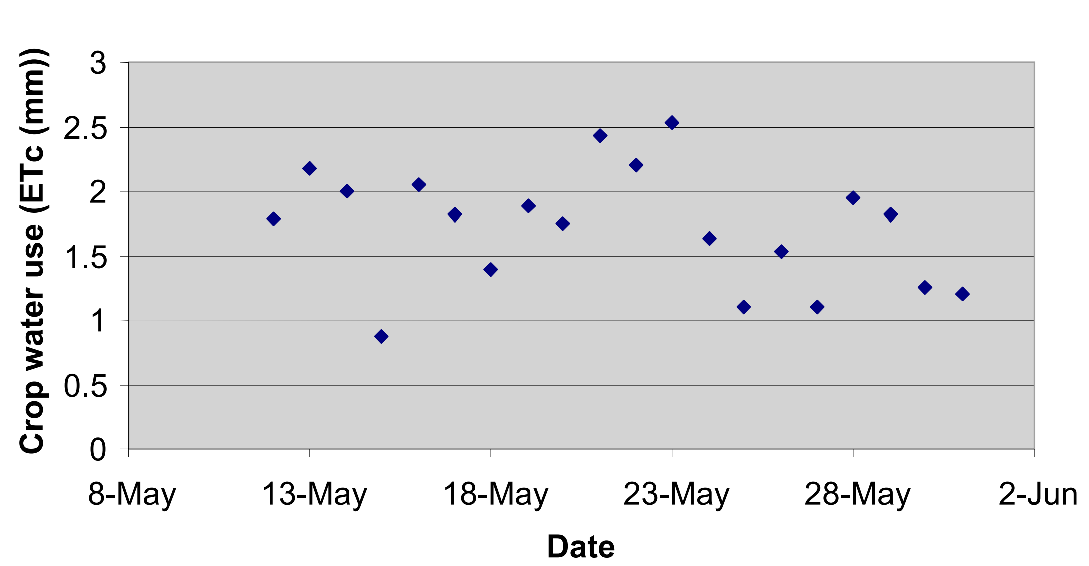


Figure 4. Daily ETc of Coyote bush at Marin

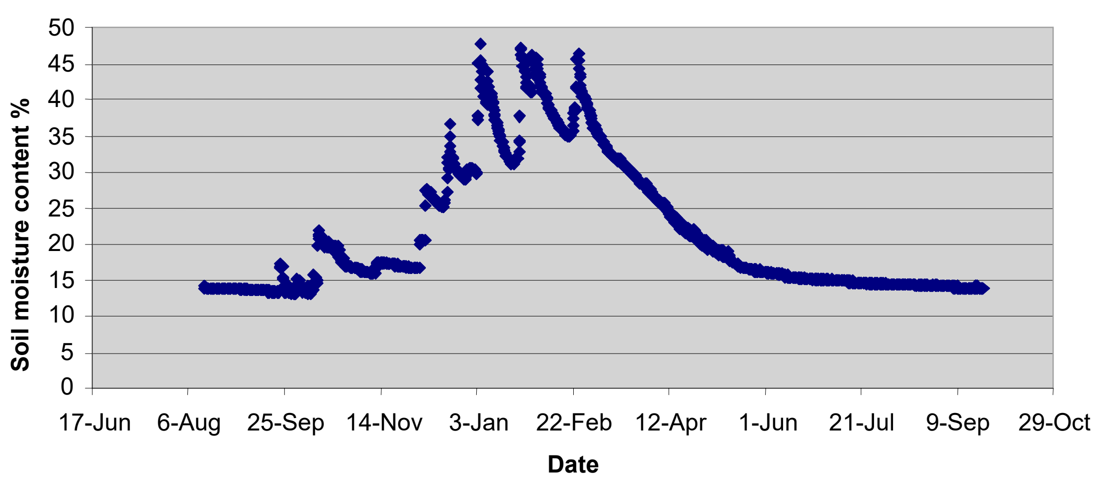
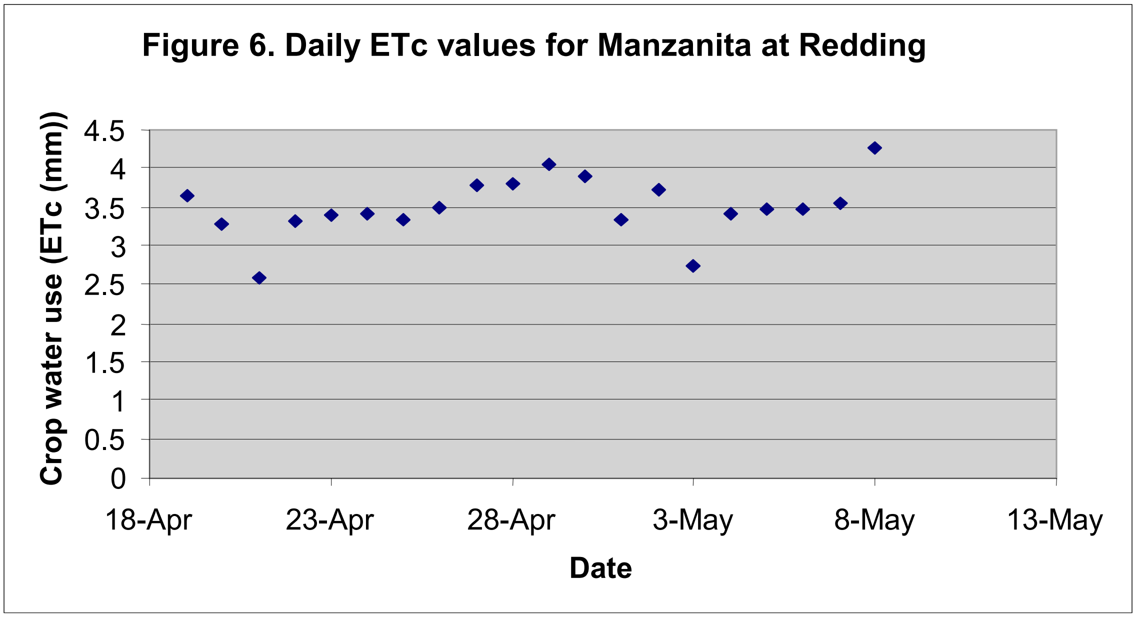
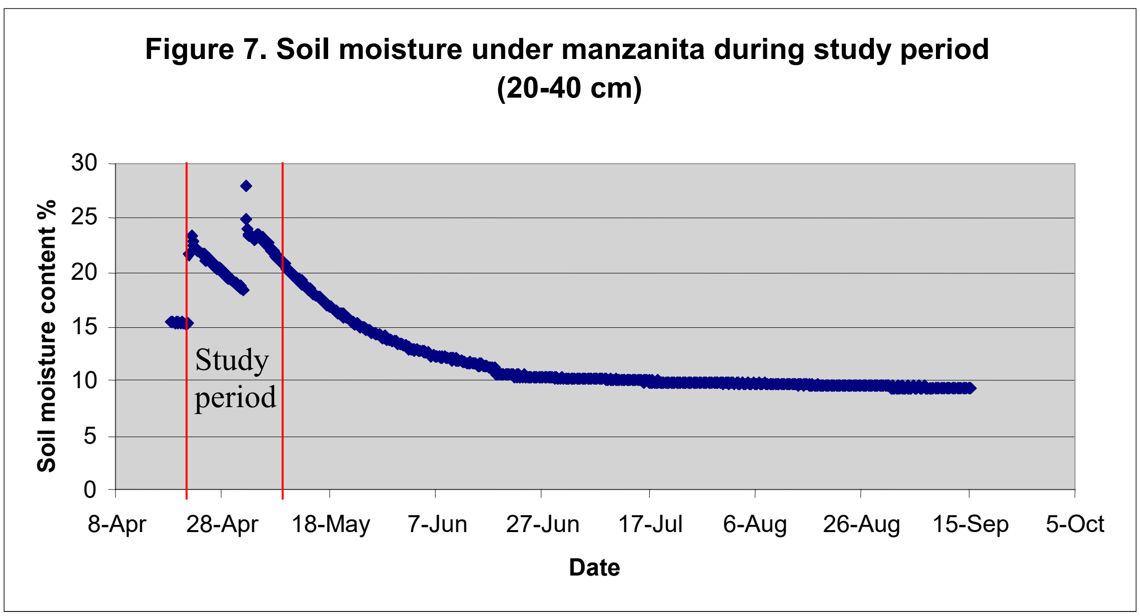


Figure 5. Soil moisture under coyote bush at Marin site one year after research period (20-40 cm)

Daily water use for manzanita remained relatively steady over the study period (Figure 6). These measurements were taken early in the spring and soil moisture did not appear to be limiting (Figure 7). The Kc determined for manzanita was 0.71. This value is a reasonable value because manzanita is a shrub that is adapted to droughty conditions. Even during periods of easily available water, it will be conservative in its water use so that soil water resources are available later in the growing season.





The results from the sage brush were similar to those of the coyote bush. The daily water use was quite low and appeared to decrease during the study period (Figure 8). Soil moisture in Figure 9 shows that most of the available water had already been exploited by the time the study was conducted. As a result the Kc value was very low (0.12). Steinwand et al. (2001) found that sage brush at a similar density (~35 %) had a Kc of 0.36. Measurements at both the coyote bush and sage brush sites were performed after the plants had already began to reduce their water use because of low soil moisture conditions. Only the Kc value measured for manzanita is usable for future modeling.

Figure 8. Daily ETc of Sage Brush at Alturas

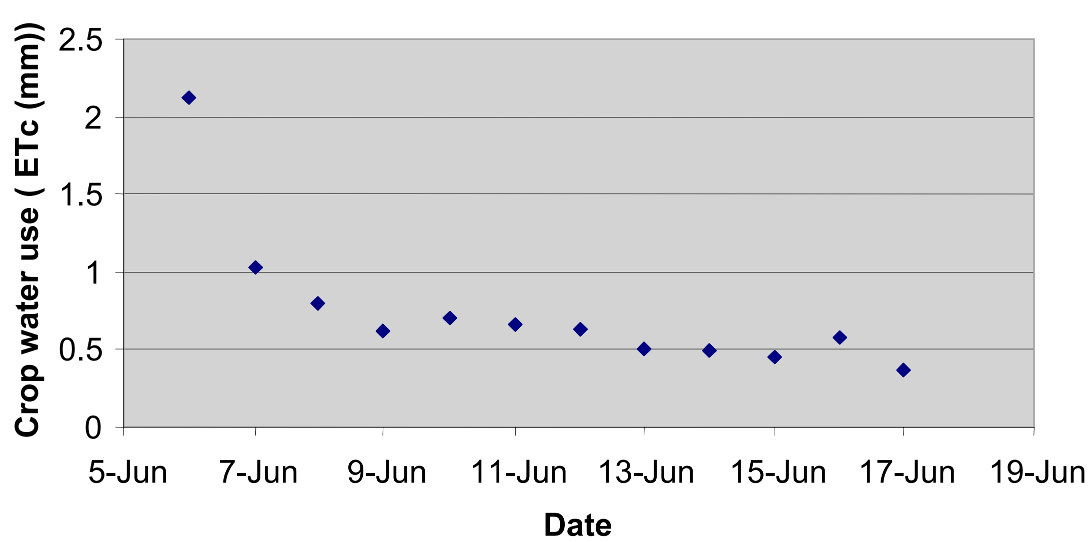


Figure 9. Soil moisture under sage brush during study period (20-40 cm)

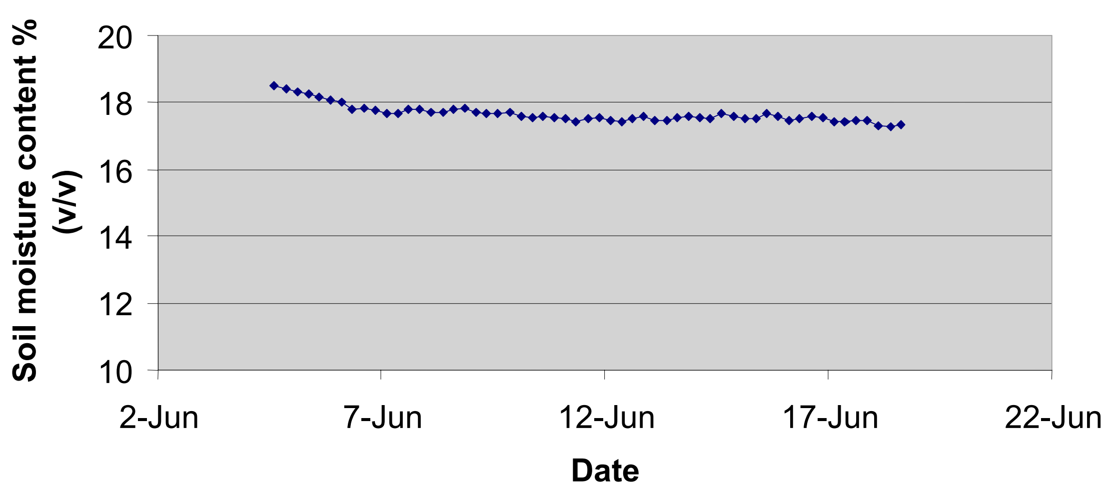


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Table 2. Water stress thresholds for three shrubs as determined by soil moisture

Plant Type	Maximum soil moisture	Start of water stress	Minimum soil moisture	% of PAW when Ks < 1
	%	%	%	%
Coyote Bush	35	21	14	67
Manzanita	23.5	18	9.5	39
Sage Brush	n/d	n/d	n/d	n/d

Soil moisture levels at which water use is reduced were evaluated for two out of the three plants (Table 2). Coyote bush and manzanita started to reduce water use when 67 and 39 % of the PAW in the soil was depleted. This data is in good agreement with the value determined for coyote bush that was previously determined at Highway 4 (60 %). The value for manzanita shows that this plant is much more conservative in its use of water resources. While most of the PAW is still in the profile, it begins to reduce water use to insure adequate supplies later in the season. Soil moisture data from the sage brush site was lost. It is presumable that an extreme xerophite like sage would begin to reduce water even earlier than manzanita. It is also presumable that given the extremely low precipitation in the regions that sage brush is found that the soil never becomes saturated like we see in the soil moisture graphs of the other locations (Figures 2 and 4). Future studies evaluating soil moisture data will show if this type of graphical determination of when water use is reduced can be determined for sage brush.

Conclusions

Practical limitations did not allow all the measurements to be taken at the same time. Only one micro-met station was available so it had to be used at all the locations. We monitored the Redding site first because it usually becomes dry there before Alturas and Marin. Measurements at Alturas were done last of all since spring comes later than most of the rest of the state. There was snow on the ground at Alturas in the month of May. If measurements were made too early in the spring the plants would not be very active and measurements would not be meaningful. A balance must be struck between allowing the weather to warm up (soil water resources are already mostly depleted) where the plants begin to become active and measuring early in the spring when water is not limiting but plants are not fully active.

Future work should focus on gathering multiple eddy covariance stations so that several locations could be monitored over the early spring season. The window of opportunity for these types of measurements is not large. The equipment used is expensive and requires an experienced technician to operate. However, this method provides much needed information that has great practical importance to revegetation efforts along California's roadsides. Funding was not provided to this project in order to perform a second year of monitoring in order to determine more meaningful Kc values for coyote bush and sage brush. In summary, the Kc value determined for manzanita can be regarded as being accurate as well as the points of water stress for coyote bush and manzanita. These values can be used in water use models with confidence.

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Appendix Section G. Evapo-Transpiration Model Specific to California's Roadside Vegetation

Synopsis

This section describes the process used to estimate water use and supply for growing wildland shrubs in field conditions without supplemental irrigation.

Introduction

The Penman-Monteith evapo-transpiration model has been described in detail in other appendix sections of this report. It is the most widely accepted physically based model and is used all over the world to estimate crop water use:

(http://www.fao.org/docrep/X0490E/x0490e06.htm)

This model is very versatile and can be modified to be used for almost any environment. Previous sections in this report have examined its application for wildlands plants growing along roadsides. Identifying model parameters (Kc and Ks) for these types of plants is not easy but if accomplished will help to insure sustained vegetation along roadsides to meet mitigation requirements by specifying the needed soil water resources.

Data requirements for this model include three types of data: plant specific parameters (Kc and Ks), site specific weather information (precipitation, ETo) and site specific soil information (PAW, depth, surface cover). The goal of this model was to be able to predict the depth of soil needed at a given roadside location so that an appropriate mitigation plant could become established at a known density. This model could be set up in a way that the Caltrans Landscape Architects could easily (with minimal training) use an interactive CD to choose a location off a California road map and be presented with a tabulated list of options, depending on plant type, plant cover and soil texture, that specifies the depth of soil required to provide adequate soil water resources.

Methods

Plant specific parameters:

Three plants were chosen to use as inputs into the model. These were coyote bush, manzanita and sage. Parameters were either experimentally determined or values from published research studies were used. The Kc value for coyote bush (1.36) was determined using the surface renewal technique as reported in section 9 of this report. In section 10 the eddy covariance technique was used to determine the Kc value of manzanita. For sage brush a value from the literature was used since no acceptable experimental value was determined. The literature review in section 8 showed that sage brush had a Kc value of 0.36 at a plant cover of 35 % (Steinwand et al., 2001). The assumptions of the model state that the Kc values should be for 100 % cover. The model we used uses a vegetation density coefficient (Kd) to predict how ETc is influenced by % cover, where greater than 70 % cover does not differ than 100 % cover:

$$Kd = \sin((\%\ cover/70)*(Pi/2)).$$

The Kc of sage brush at >70 % density can then be determined using the relationship:

$$Kc_{(>70\ \%\ cover)} = Kc_{(35\ \%\ cover)}/Kd$$

In this way, the Kc of sage brush with calculated to be 0.51.

This same equation is used in the model when the % cover of the plant is specified to be below 100 %. Since a surface mulch is assumed to be used on all sites to reduce competition and evaporation, a reduction in cover results in more water resources for the plants that are there. This is intuitive since we see sparse vegetation on soils with little soil water resources.

The point at which the plants begin to reduce water use was characterized as a function of at what % of their PAW they began to reduce water use. It was at this point that the Ks values became less than 1. The Ks values dropped at a predictable rate after this point as specified by the model. For coyote bush this point occurred when 60-67 % of its PAW was depleted (data from section 9 and 10). An average value of 63.5 % was used in the model for coyote bush. Manzanita began to reduce water use when 39 % of the PAW was depleted according to soil moisture data in section 10. No reliable data was obtained either experimentally or from the literature concerning sage brush. For lack of a better method we gave an educated guess (30 % PAW) for modeling purposes.

Site specific weather information:

In order to calculate daily water depletion from a roadside, the local ETo and precipitation data need to be known. Monthly ETo and annual precipitation data for California, based on long-term averages, were converted to average daily values using a curve fitting technique. Values for ETo were taken from a statewide ETo map available from the California Irrigation Management Information System.

http://www.cimis.water.ca.gov/cimis/images/etomap.jpg

Annual precipitation values for zones around the state were taken from a map created by the California Department of Forestry.

http://frap.cdf.ca.gov/webdata/maps/statewide/rainmap.pdf

Generalized zones of ETo and precipitation were then identified, however it must be understood that each zone represents a range of values and predicted values may under or overestimate the actual value. Greater resolution in zonation was intended to minimize this error. Furthermore, during years where solar radiation or precipitation deviate from their historical averages, there will be a greater amount of error in model estimates.

Site specific soil information:

The amount of PAW in the soil was estimated using equations based on soil texture developed by Saxton et al. (1986). Soil texture can either be determined by a soil laboratory as is usually done for a standard geo-tech study or estimated by feel or looked up in a soil survey manual. The amount of PAW in a soil profile can be adjusted if there are a significant amount of coarse fragments (rocks > 2mm in diameter). It is generally assumed that rocks do not contribute a significant source water to plants in the soil profile, although this depends of the type of rock. Porous sedimentary rocks (silt stones, fine sandstones) can hold significant amounts of moisture, although the diffusion of moisture out of these rocks is slow. Impermeable rock types (quartzite, competent extrusive volcanic or granitic clasts) hold nearly no water.

Once the impermeable rock content is determined on a volumetric basis, then this fraction of the total soil volume can be subtracted from the volumetric PAW content. Many road-cuts consist of sub-grade material and therefore contain a significant portion of rock fragments. If this is not taken into account there will be an overestimation in PAW. In practice, the depth of soil required for a specific plant type at a given density must be multiplied by 1 plus the fraction of rock content to account for this loss of PAW.

The main output variable in the model is soil depth. The depth of the soil is variable depending on the soil resources needed for a given plant type at a specific density at a desired location. The details of the inner workings of the model are not presented in this report, but a much more detailed description of the water use model used in this project can be found at:

http://biomet.ucdavis.edu/irrigation_scheduling/LIMP/limp.pdf

Conclusions

This project was initiated to develop appropriate techniques for the establishment of vegetation along roadsides that will not require supplemental irrigation. Plant types were identified that are drought adapted and suitable for a variety of regions in California. Parameters needed to apply the Penmen-Monteith evapo-transpiration model to these plants were determined and a model was developed that can specify the depth of soil needed to grow a plant type based on local climate data and the available soil water resources. Landscape Architects can use this tool when determining slope specifications so that long-term mitigation goals can be met without the need for supplemental irrigation.

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