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Evapotranspiration of two vegetation communities in a high-elevation riparian meadow at Hart Prairie, Arizona

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[1] Hart Prairie, Arizona, has the largest Bebb willow (*Salix bebbiana*) community in the United States; however, greater than 95% of willows are older than 80 years and regeneration by seed is not occurring. This study examined the evapotranspiration of two herbaceous communities that dominate the Hart Prairie watershed: (1) a mixture of bracken fern (*Pteridium aquilinum*) and graminoids and (2) dominantly graminoids. Transpiration during premonsoon and postmonsoon dry periods of 2000, 2001, and 2002 was estimated for each community by the difference in volumetric soil-water content (0–30 cm soil depth) between replicated plots that were clipped of all vegetation and control, unclipped plots. Transpiration rates estimated under conditions of minimal soil drainage varied between 0.63 and 2.4 mm/d for the fern-graminoid community and 0.57 and 1.1 mm/d for the graminoid community over the study. The fern-graminoid community produced more biomass than the graminoid community in all years, but generally had lower transpiration rates. Severe drought in year 2002 reduced growth and transpiration of the fern-graminoid community more than the graminoid community. Evaporation rates were estimated by temporal changes in soil-water content in clipped plots during dry periods, and were 54 to 474% of transpiration rates estimated under conditions of minimal soil drainage because of the dry and windy conditions that occur at the study site. Based on this study and a study of transpiration of scattered trees invading the meadow, transpiration by the herbaceous understory was higher than transpiration by trees during similar seasons.

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1. Introduction

[2] Dense herbaceous vegetation in the arid western United States can influence water recharge into deep soil and groundwater [*Bosch and Hewlett*, 1982; *Huxman et al.*, 2005]. For example, removal of grass in a Colorado prairie allowed soil water in the upper layers to infiltrate deeper into the soil [*Dodd et al.*, 1998]. Soil-water storage at three sites in the arid western United States (Beatty, NV, Las Cruces, NM, and Hanford, WA) was lower in vegetated versus unvegetated sites [*Gee et al.*, 1994]. Water use by bracken fern (*Pteridium aquilinum*), a common component of the herbaceous understory in our study, can be about half of total forest transpiration (T) under hot, dry conditions [*Tan and Black*, 1976; *Roberts et al.*, 1980]. Current proposals for watershed restoration in some southwestern U.S. forests are based on the assumption that tree thinning will reduce evapotranspiration (ET) and consequently increase runoff and groundwater recharge [*Covington and Moore*, 1994]. However, high transpiration rates of the herbaceous understory may reduce effects of tree thinning on runoff and recharge.

[3] The purpose of this study was to estimate evapotranspiration of the herbaceous understory of Hart Prairie, a high-elevation wet meadow in a semiarid western U.S. watershed. Understanding the water balance of Hart Prairie is important because it supports a rare riparian community of Bebb willow (*Salix bebbiana*) that is not regenerating by seed, likely because of low soil-water availability [*DeWald and Springer*, 2001]. Hart Prairie is an important Bebb willow community because it is thought to be the largest such community in the United States [*Waring*, 1992a, 1992b] and is located at the southern extent of the species range [*Kearney and Peebles*, 1951]. Most Bebb willow at Hart Prairie are older than 80 years and young willow are sparse [*Waring*, 1992a, 1992b; *DeWald and Springer*, 2001]. Factors suggested to limit willow regeneration include heavy herbivory from elk and deer, competition from herbaceous vegetation and encroaching pines, low soil-water availability, and lack of high stream flows [*DeWald and Springer*, 2001]. *DeWald and Springer* [2001] hypothesized that drought, surface-water diversions, and high water use by herbaceous plants and the upslope coniferous forest have reduced water availability to the Bebb willow community and may limit willow regeneration by seed.

[4] The sources of variation in evapotranspiration that we addressed were herbaceous vegetation community type,

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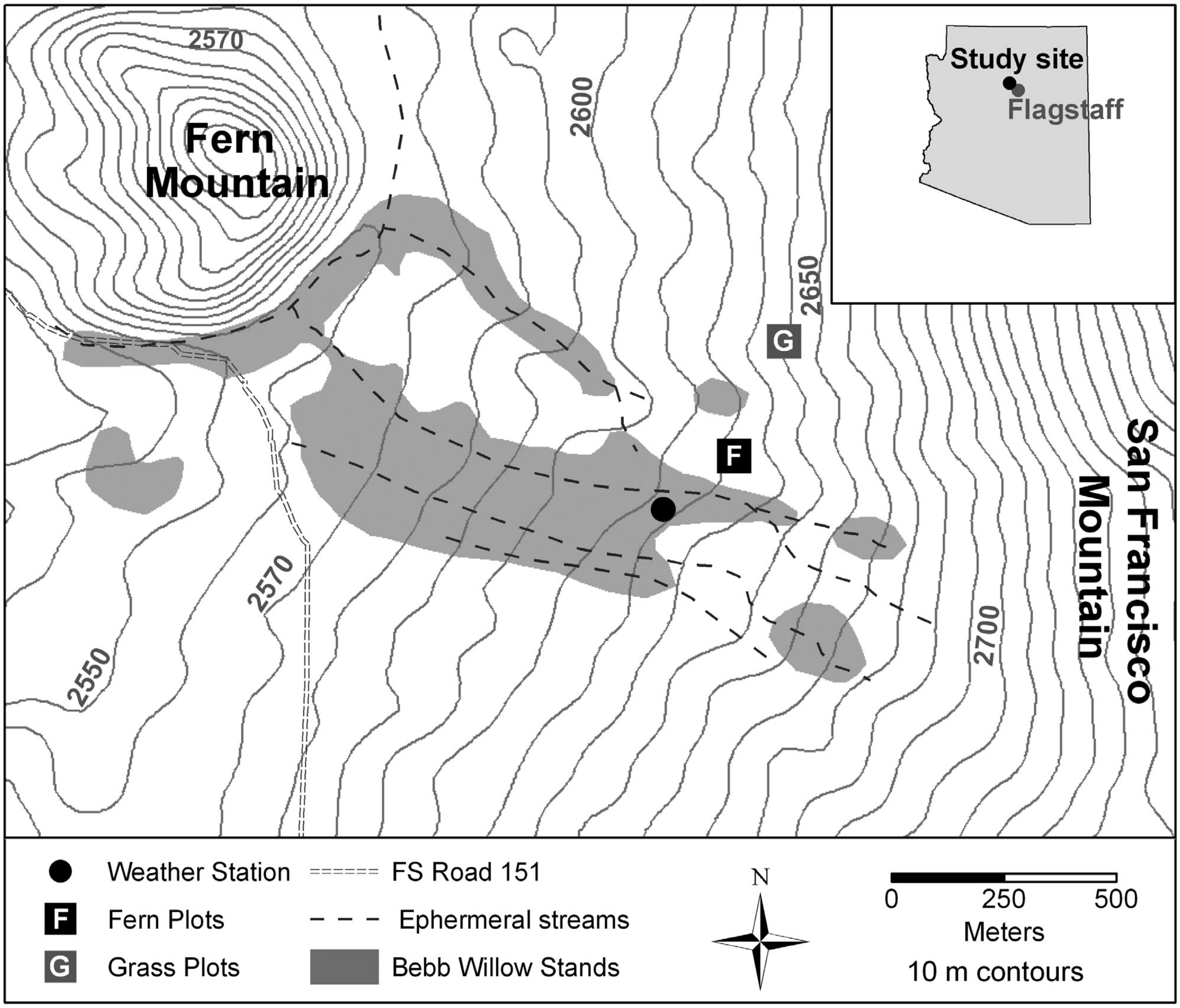

Figure 1. Map of Hart Prairie showing the locations of the Bebb willow community, herbaceous vegetation evapotranspiration plots, and weather tower.

year of measurement, and season of measurement. We hypothesized that transpiration of the herbaceous understory was lower than the transpiration of a low density pine forest which was encroaching onto the wet meadow. Watershed runoff studies suggest that encroachment by woody vegetation into grasslands often increases evapotranspiration, with the largest increases occurring in more humid and mesic environments [*Bosch and Hewlett*, 1982; *Zhang et al.*, 2001]. However, the effect of woody encroachment on evapotranspiration in more arid environments is less clear, with the direction and magnitude of the effect depending on interactions among characteristics of vegetation, landscape, and climate [*Huxman et al.*, 2005]. Based on previous watershed studies, we hypothesized that growing-season transpiration rate of the herbaceous understory would be lower than transpiration rate of the pine forest that has encroached into Hart Prairie. The low-density stand (average of 16 trees/ha) of ponderosa pine (*Pinus ponderosa*) and limber pine (*Pinus flexilis*) that has encroached into Hart Prairie upstream of the Bebb willow community had a 60-day growing-season stand transpiration between 3.5 mm and 14.2 mm in 2000 based on tree sapflow scaled to the stand level [*Fischer*, 2001; *Fischer et al.*, 2002]. However, transpiration of the herbaceous understory had not previously been measured.

2. Study Site

[5] Hart Prairie is located 24 km northwest of Flagstaff, Arizona (35°22′N, 111°45′W, Figure 1) on the west side of San Francisco Mountain in the U.S. Forest Service Fern Mountain Botanical Area and in The Nature Conservancy Hart Prairie Preserve. It covers an area of 101 ha between elevations of 2570 m and 2743 m. Humphreys Peak is the highest elevation in Arizona (3850 m) and the top of the Hart Prairie watershed. The Hart Prairie watershed discharges through Hart Creek, at the base of Fern Mountain (Figure 1). Hart Creek flows into Volunteer Wash, which is a tributary of the Verde River. The area of the Hart Creek watershed is 12 km^2 [*Gavin*, 1998].

[6] Hart Prairie is an upland riparian area dominated by Bebb willow, trembling aspen (*Populus tremuloides*), and

Table 1. Scientific and Common Names and Photosynthetic Pathway of the Most Dominant Five Plant Species by Percent Cover in the Fern-Graminoid and Graminoid Communities, Measured September 29, 2000 (n = 6 Plots per Community)[a]

Community	Scientific Name	Common Name	Photosynthetic Pathway	Mean % Cover (1SE)
Fern-graminoid	Pteridium aquilinum	Bracken fern	C3	31.7 (3.07)
	Poa pratensis	Kentucky bluegrass	C3	30.0 (8.17)
	Bromus anomalus	Nodding brome	C3	17.9 (7.54)
	Taraxacum officinal	common dandelion	C3	2.5 (0.65)
	Vicia americana	American vetch	C3	1.3 (0.56)
Graminoid	Festuca arizonica	Arizona fescue	C3	21.7 (8.03)
	Muhlenbergia montana	Mountain muhly	C4	8.4 (5.42)
	Geum triflorum	prairiesmoke	C3	5.8 (1.54)
	Poa pratensis	Kentucky bluegrass	C3	2.5 (0.65)
	Bromus anomalus	Nodding brome	C3	1.7 (0.83)

[a] In addition to the listed species, 10 other herbaceous species in the fern-graminoid community and 20 in the graminoid community occurred at average cover <1%. Photosynthetic pathway for the grasses was obtained from *Watson and Dallwitz* [1992].

mixed graminoid communities [*DeWald and Springer*, 2001]. These aspen and Bebb willow communities are important for biodiversity and wildlife habitat [*Naiman et al.*, 1993; *DeWald and Springer*, 2001]. Other trees present in the willow community at Hart Prairie are ponderosa pine, limber pine, and Englemann spruce (*Picea engelmannii*). The understory consists of meadow grasses and forbs such as bracken fern, Kentucky blue grass (*Poa pratensis*), Arizona fescue (*Festuca arizonica*), and silver lupine (*Lupinus argenteus*). A survey of plant species in both communities performed in late September 2000 (n = 6, 1 m × 0.25 m plots per community [*Amentt*, 2002]) showed that the fern-graminoid community included about 15 herbaceous species, and cover was dominated by bracken fern, Kentucky bluegrass, and nodding brome (*Bromus anomalus*) (Table 1). All dominant species in the fern-graminoid community have the C3 photosynthetic pathway. The graminoid community was more diverse, with about 25 herbaceous species, and cover was dominated by Arizona fescue (*Festuca arizonica*)(C3 pathway) and mountain muhly (*Muhlenbergia montana*)(C4 pathway) (Table 1).

[7] The hydrogeology of Hart Prairie consists of small-perched aquifers. Highly permeable alluvial and colluvial deposits derived from volcanic parent materials are common [*Dewitt*, 1980; *Gavin*, 1998]. The western slope of San Francisco Mountain has accumulated thick colluvial deposits from the different stages of volcanism of San Francisco Mountain [*Robinson*, 1913; *Updike and Pewe*, 1970; *Holm*, 1986]. Clay lenses in the alluvial and colluvial deposits allow thin, ephemeral, and discontinuous perched aquifers to form [*Dewitt*, 1980]. Recharge from these small perched aquifers is directly related to the annual amount of snow and rain. Because storage in these perched aquifers is greatly diminished in dry years, recharge must happen frequently [*Dewitt*, 1980]. Snowmelt is the primary source of recharge for Hart Prairie, but heavy monsoon season rains in late summer can also provide limited recharge to some of the small-perched aquifers in Hart Prairie. *Robinson* [1913] noted that springs were the most reliable water source in the San Francisco Volcanic Field. The sources for these springs are shallow, small-perched aquifers, because the regional aquifer in the Coconino Sandstone and Supai Formation is at least 1000 m below land surface [*Gavin*, 1998].

[8] The volcanic rocks in the area are primarily basalt [*Holm*, 1988]. Debris flows from San Francisco Mountain comprise the colluvial deposits that underlie Hart Prairie [*Holm*, 1988]. Soils in Hart Prairie are classified as loamy-skeletal, mixed, frigid Argiaquoll, and a fine-loamy, mixed Aquic Argiboroll [*Gavin*, 1998]. The Argiaquoll, very cobbly loam to very cobbly clay loam soils contain up to 50% clay and are primarily located around the springs. The majority of the soils are classified as Argiborolls, and are characterized by an over-thickened mollic epipedon. The fern-graminoid and graminoid plots have a saturated hydraulic conductivity of 1.2×10^{-3} cm/s and 6.1×10^{-4} cm/s and a field capacity of approximately 30% and 26%, respectively [*Amentt*, 2002].

[9] The climate of Hart Prairie is semiarid. The closest meteorological station is Fort Valley, Arizona, 330 m lower in elevation and 13 km away (35°16′N, 111°44′W). The monthly average temperature at Fort Valley varies between −3.6°C in the winter and 16.9°C in the summer and the mean annual temperature is 6°C (based on 92 years). There are two wet seasons, winter and summer, and average annual precipitation is 579 mm (includes water equivalent for snow fall). The majority of the precipitation comes during the winter as snow, averaging 2167 mm annually (Western Regional Climate Center, http://www.wrcc.dri.edu). The "monsoon" showers come between late June and September. The driest months of the year are late April to mid June and late August to October.

3. Methods

3.1. Precipitation

[10] Precipitation at Hart Prairie was measured (accuracy ± 0.13 mm) with a Rain Wise model RGEL Electronic Recording tipping bucket and accompanying data logger (Rain Wise, Inc., Bar Harbor, ME) at an elevation of 2810 m at the upper end of Hart Prairie (Figure 1). The bucket was equipped with a heating blanket that melted snow in the winter to allow measurement of snowfall in water equivalents. Also, historic yearly precipitation totals were estimated for Hart Prairie based on linear regression ($r^2 = 0.79$) between empirically measured yearly precipitation at Hart Prairie and yearly precipitation measured at the Fort Valley

weather station (Western Regional Climate Center, http://www.wrcc.dri.edu).

3.2. Groundwater Levels

[11] Groundwater levels were measured in many shallow wells in the Hart Prairie area, but water levels from a 1.5-m deep well at the weather tower (Figure 1) were used to represent groundwater conditions at the adjacent herbaceous study plots. Water levels in the well were measured with a chalked, etched steel tape with an accuracy of ±0.15 cm about every two weeks during the growing season and monthly during the winter.

3.3. Herbaceous Transpiration

[12] Herbaceous communities inhabiting Hart Prairie vary spatially depending on water availability and elevation. In the wetter areas and lower elevations, bracken fern and several graminoid species dominate the herbaceous community. Upslope and in drier areas, the understory is dominated by graminoids with no ferns (Table 1). The same experiment was performed in the mixed bracken fern-graminoid community and in the graminoid community (Figure 1).

[13] We estimated transpiration from each herbaceous community by comparing volumetric soil-water content (θ) between paired plots that differed in aboveground herbaceous vegetation (present or absent). This approach has been used successfully to measure transpiration by short-grass prairie in Colorado [*Dodd et al.*, 1998]. Five blocks were randomly established in each community on a 7° slope. Each block contained two circular plots (1.7 m radius); one was used as the unclipped, control and the second plot was clipped. All aboveground herbaceous vegetation in the clipped plots was removed weekly between May and September of each year by hand clippers and with a gas-powered weed cutter. Clipped biomass was left on the soil surface to mimic the cover of the unclipped plots. After the first year of the study, there was little vegetation to clip in the clipped plots.

3.4. Soil Water

[14] Volumetric soil-water content was measured weekly with a Moisture Point MP-917 time-domain reflectometry system (Environmental Sensors, Inc., Vancouver, BC). This instrument has a measurement range between 10% and 90% θ with an accuracy of ±3% in most soil conditions without calibration. Measurements were made weekly in each plot between May and September of 2000, 2001, and 2002. Thirty-centimeter probes were used because they extended below the rooting depth of most of the herbaceous vegetation, as indicated by the absence of roots below this depth in several hand-dug holes, but remained in the thick B horizon of the soils. Two pairs of 30 cm probes were inserted in the ground near the center of each plot to decrease influences of water uptake from outside the plot. All plots were located at least 20 m from trees to eliminate influences of water uptake by trees. Limited data suggest that lateral roots of ponderosa pine extend to a maximum of about 40 times the diameter of the tree at breast height [*Curtis*, 1964]. Measurements of θ at two locations within each plot were averaged for each plot.

3.5. Herbaceous Biomass

[15] Aboveground biomass was sampled near the end of the growing season when biomass peaked (October 2, 2000, September 20, 2001, September 25, 2002). All living aboveground vegetation was collected from a 0.43-m^2 area adjacent to each block in each of the two vegetation communities (Figure 1). The vegetation was dried at 70° C for 24 hours prior to weighing.

3.6. Analysis

[16] Transpiration (T) was estimated for each herbaceous community type by comparing the differences in θ between the unclipped and clipped plots during distinct drying periods when there was no precipitation. Two such periods occurred in each year (2000, 2001, and 2002) of the study: late April to mid June (premonsoon dry period), and late August to late September (postmonsoon dry period). Although analysis of hydrographs from groundwater wells in Hart Prairie suggests that no recharge to the aquifer or possible lateral flow occurred during these dry periods, there may have been a drainage when θ exceeded the field capacity. Evaporation (E) was measured for the clipped plots and E and T for the unclipped plots. The mean difference in θ between the unclipped and clipped plots at the end of each dry-down period was used to estimate T during each dry-down period. We could not estimate T during the rainy monsoon season (mid June to August) with this method because some precipitation may have drained below 30 cm in the soil and flowed laterally. Volumetric soil-water content was converted to depth in centimeters to determine T and to compare it to precipitation. Evaporation rates were estimated by the temporal change in θ during periods of no precipitation (premonsoon and postmonsoon dry periods) in the clipped plots by linear regression of θ on day of the year. Drainage rates were estimated using *Clapp and Hornberger* [1978].

[17] Estimates of herbaceous T during the premonsoon and postmonsoon dry periods were compared with potential evapotranspiration (PET) estimated by the *Hamon* [1963] method. *Hamon* [1963] is a reference surface PET method which uses an empirical function of the day length and the saturation vapor pressure at the mean daily temperature. A recent comparison of potential evapotranspiration functions showed that the Hamon method had the lowest mean annual error and the smallest bias over a gradient of aridity of five reference-surface methods [*Vorosmarty et al.*, 1998]. PET rates with the *Hamon* [1963] method were calculated for the premonsoon and postmonsoon dry periods to be directly comparable with the dry-down periods used to calculate the herbaceous E and T rates.

[18] Vapor pressure deficit (VPD) was calculated for each premonsoon and postmonsoon drydown period from mean daytime (8:00 to 17:00) air temperature and dew point temperature at the Flagstaff, Arizona, recording station at Pulliam Airport (the nearest uninterrupted, complete data set). Vapor pressure deficit was calculated to be the difference between the mean saturated vapor pressure of the mean daytime temperature during the drydown period, minus the vapor pressure at the mean daily dew point temperature [*Murray*, 1967].

[19] Volumetric soil-water content data were analyzed with multivariate analysis of variance (MANOVA) with repeated measures using SAS JMP 4 software (SAS Institute, Inc., Cary, NC). We analyzed the data separately by year. Measurement date within the year was the repeated

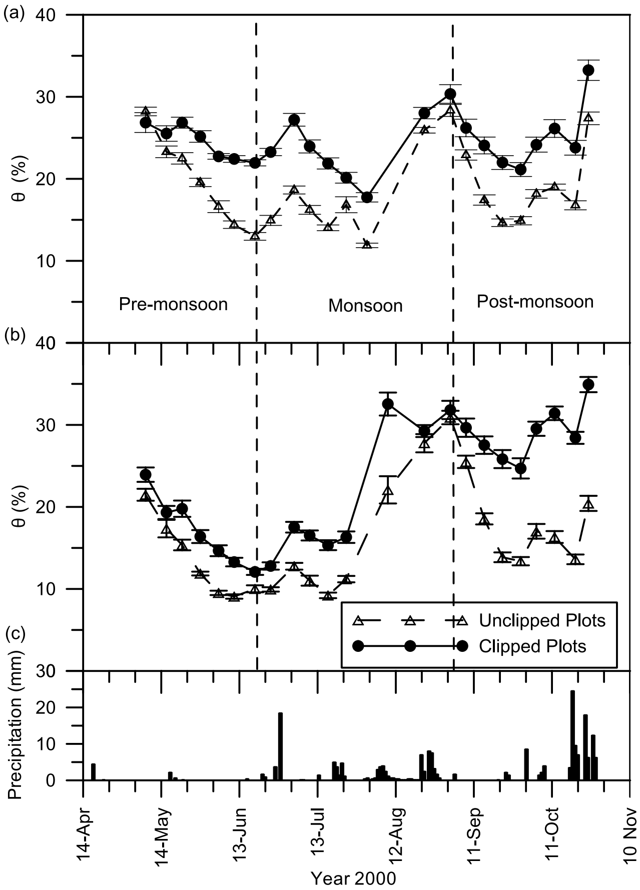

Figure 2. Mean soil-water content (θ) in the (a) fern-graminoid community and (b) graminoid community, and (c) total daily precipitation for the 2000 growing season. Error bars represent one standard error of the mean. Vertical lines show the beginning and end of monsoon season.

factor. Sources of variation in the MANOVA for each year were: community type, treatment, block, and the community x treatment interaction. The effect of measurement date could not be tested directly due to limitations of the degrees of freedom that can occur when the number of levels of the repeated factor greatly exceeds the number of replications. Biomass data were analyzed with ANOVA using SAS JMP 4 (SAS Institute, Inc. Cary, NC). The sources of variation were year, community, block, and the community x year interaction. Mean separations of the biomass data were performed with Duncan's New Multiple Range test at p = 0.05.

4. Results

4.1. Precipitation

[20] Total precipitation measured in Hart Prairie between October 1999 and September 2000 (the year 2000 water year) was 293 mm, 51% of the average annual precipitation of 569 mm/yr based on a 92 yr record at the nearby Fort Valley Climate Center, AZ. The monsoon season began on June 19, 2000 (Figure 2c). Total precipitation between October 2000 and September 2001 was 440 mm, 77% of annual average precipitation, but not as low as 2000. The monsoon season began on June 20, 2001 (Figure 3c). Rain showers were more frequent in 2001 compared to 2000 (Figures 2c and 3c). Total precipitation between October 2001 and September 2002 was 206 mm (36% annual average), the lowest of all years included in the study and one of the driest on record for the region. During the last year of the study, the monsoon began the latest of the three years, July 9, 2002 (Figure 4c).

4.2. Groundwater Levels and Drainage

[21] In 2000 and 2001, water levels in the shallow well were at or near land surface after snow melted in early spring (Figure 5b). Water levels declined in 2000 and 2001 until the well went dry (>1.5 m depth to water), typically in June or July. In 2002, the well was dry the entire growing season. In all years, water levels in the well were below the depth of θ measurements (30 cm) when θ measurements started in April or May (Figures 5a and 5b). Although water levels were below 30 cm, there likely was some drainage when θ exceeded the field capacity. Drainage was greatest at the beginning of the drydown periods, especially during 2001, and during the beginning of the postmonsoon drydown period each year. We estimated that drainage rates

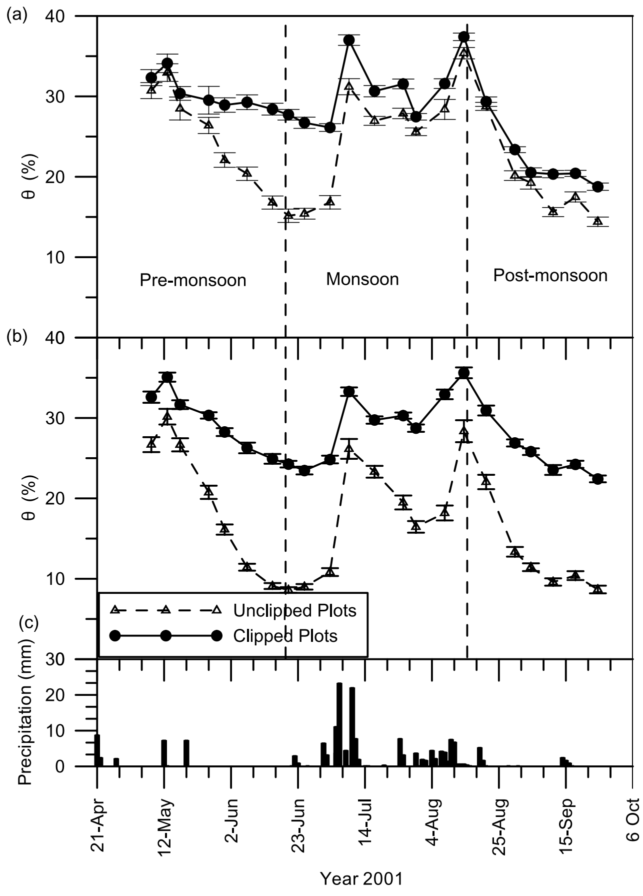

Figure 3. Mean soil-water content (θ) in the (a) fern-graminoid community and (b) graminoid community, and (c) total daily precipitation for the 2001 growing season. Error bars represent one standard error of the mean. Vertical lines show the beginning and end of monsoon season.

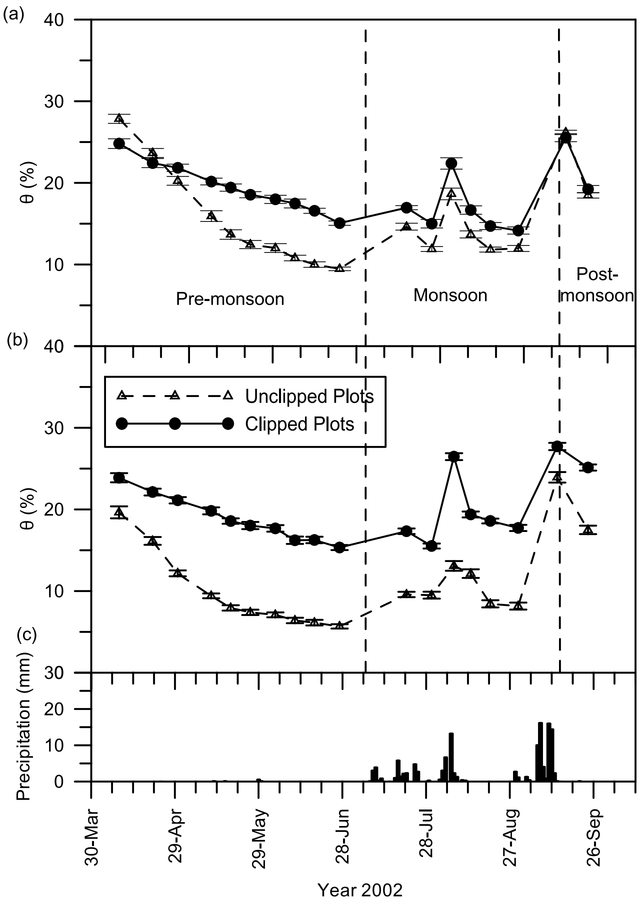

Figure 4. Mean soil-water content (θ) in the (a) fern-graminoid community and (b) graminoid community, and (c) total daily precipitation for the 2002 growing season. Error bars represent one standard error of the mean. Vertical lines show the beginning and end of monsoon season.

became significant (>0.5 mm/d) when θ > 0.28 in the fern-graminoid and graminoid plots. These conditions did not exist for the 2000 or 2002 premonsoon dry-down periods, but did for the beginning of the 2001 premonsoon, and each postmonsoon dry-down period.

4.3. Volumetric Soil-Water Content

4.3.1. 2000 Growing Season

[22] The plots were initially clipped on May 1, 2000, and θ data collection started on May 8, 2000. The growing season had two distinct dry-down periods: premonsoon (May 13 to June 19) and postmonsoon (September 2 to September 22) (Figures 2a and 2b). Temporal variation in θ was similar in both community types (Figures 2a and 2b). Volumetric soil-water content was high in May and slowly decreased during June before the monsoon. During the monsoon, θ fluctuated with amount of precipitation, and then declined after the monsoon ended until late September when precipitation occurred (Figures 2a and 2b).

[23] In 2000, significant sources of variation in θ were community type and treatment (clipped or unclipped) (Table 2). Maximum differences in θ between treatments in the first dry-down period (May 13 to June 19) were larger in the fern-graminoid community (8.8%) (Figure 2a) than in the graminoid community (4.7%) (Figure 2b). There was a 41% reduction in θ between clipped and unclipped fern-graminoid plots at the end of the premonsoon dry-down period versus a 17% reduction for the graminoid community. This pattern was reversed at the end of the second dry-down period (September 2 to September 22) where the graminoid community reduced θ by about 46% (Figure 2b) versus 38% in the fern-graminoid community (Figure 2a).

[24] The fern-graminoid community used 90 mm of water over 37 days in the pre-monsoon period, or a T rate of 2.4 mm/day (Table 3). Transpiration rate of the fern-graminoid community was higher in the post-monsoon season compared to the premonsoon dry period when 62 mm was used over 20 days for a T rate of 3.1 mm/day (Table 3). Transpiration of the fern-graminoid community in the premonsoon and postmonsoon dry periods combined was 52% of total water-year (October-September) precipitation. For the fern-graminoid community in 2000, the E rate ranged from 1.3 mm/day (premonsoon) to 4.0 mm/day (postmonsoon) (Table 3). PET estimated with the Hamon method was 2.6 mm/d for the premonsoon dry period and 2.5 mm/d for the postmonsoon dry periods (Table 3). Actual ET estimated by summing T and E rates (AET) was greater than PET estimated with the Hamon method by 1.4 fold in the premonsoon dry period and 2.8 fold in the postmonsoon dry period (Table 3).

[25] Transpiration of the graminoid community in 2000 for the 37-day premonsoon period was 0.57 mm/day (Table 3). T of the graminoid community was higher in the postmonsoon season (5.7 mm/day) compared to the premonsoon season (Table 3). For the graminoid community, E rates ranged from 2.7 mm/day (premonsoon) to 3.0 mm/day (postmonsoon). Actual ET estimated by summing T and E rates (AET) was greater than PET by 1.2 fold in the premonsoon dry period and 3.5 fold in the postmonsoon dry period (Table 3).

4.3.2. 2001 Growing Season

[26] The 2001 results differed from the 2000 results, probably due to the wetter winter that occurred in 2000–2001 than in 1999–2000. Volumetric soil-water content measurements started on May 8, 2001 and ended on September 25, 2001. The premonsoon dry period lasted 38 days from May 13, 2001, to June 20, 2001 (Figure 3). The postmonsoon dry period lasted 28 days from August 14, 2001, to September 11, 2001 (Figure 3). In 2001, trends in θ for both herbaceous communities (Figures 3a and 3b) were similar to 2000 (Figures 2a and 2b). However, the initial decrease of θ in 2001 was greater than in 2000 because θ was higher at the beginning of the measurement period in 2001, and then reached the same low levels at the end of the premonsoon dry period as in 2000.

[27] In 2001, community, treatment, and the community x treatment interaction were significant sources of variation in θ (Table 2). The graminoid community (Figure 3b) reduced θ more than the fern-graminoid community (Figure 3a) at both dry periods. There was a 64% reduction in θ between clipped and unclipped graminoid plots at the end of the premonsoon dry-down period versus 45% for the fern-graminoid community. There was a 63% reduction in θ between clipped and unclipped graminoid plots at the end of the postmonsoon dry-down period versus 27% for the fern-graminoid community.

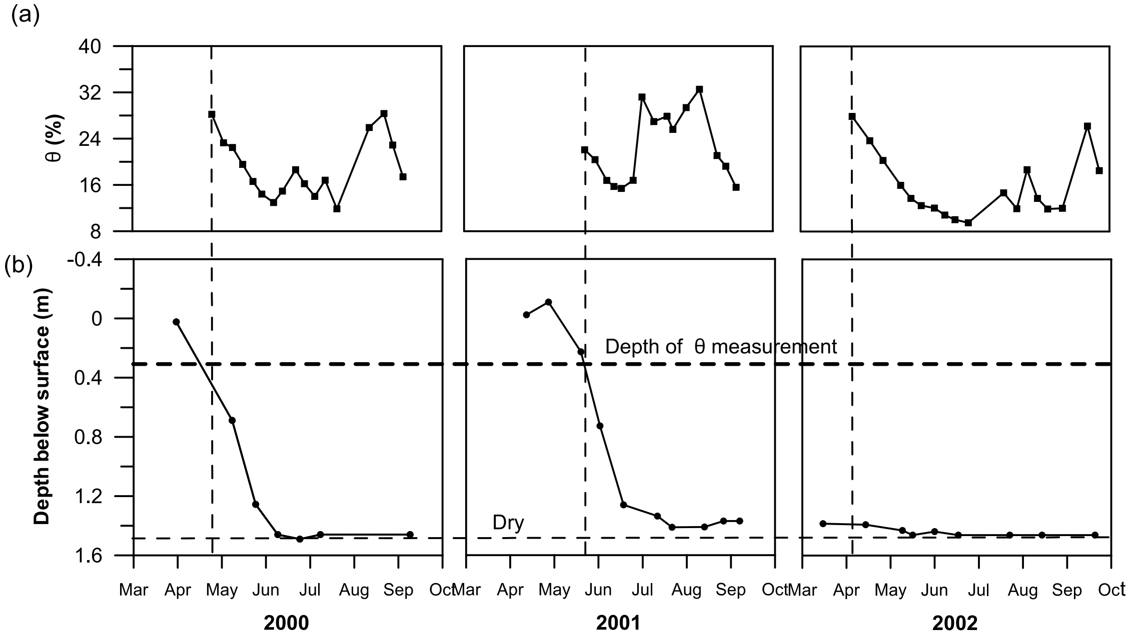

Figure 5. Mean soil-water content (θ) of unclipped plots in the (a) fern-graminoid community in 2000, 2001, and 2002 and (b) depth to groundwater in a shallow well located near the fern-graminoid community in 2000, 2001, and 2002. The depth of θ measurements (0–30 cm) is shown on depth to groundwater plot (Figure 5b).

[28] Higher precipitation in year 2001 (440 mm) versus 2000 (293 mm) generally resulted in higher θ in all community-treatment combinations in 2001 (Figures 2 and 3). Exceptions to this trend occurred in the fern-graminoid community where θ was lower in the clipped and unclipped treatments in 2001 than 2000 between late August and late September (Figures 2a and 3a), and the graminoid community where θ was lower in the unclipped treatment in 2001 than 2000 between mid July and September (Figures 2b and 3b).

[29] Transpiration in the fern-graminoid community in 2001 was 126 mm over the 38-day pre-monsoon period for a T rate of 3.3 mm/day (Table 3). The T rate for the 28-day post-monsoon period decreased to 1.7 mm/day in this community (Table 3). PET estimated with the Hamon method in both communities was 2.6 mm/d for the premonsoon dry period and 2.7 mm/d for the postmonsoon dry periods (Table 3). AET was greater than PET by 1.7 (premonsoon dry period) and 2.9 fold (postmonsoon dry period) (Table 3).

[30] The graminoid community transpired 157 mm of water during 38-day pre-monsoon period in 2001, for a rate of 4.1 mm/day (Table 3). The T rate of the graminoid community was higher in the 28-day post-monsoon season (5.0 mm/d) than in the premonsoon dry period (Table 3). E rates ranged from 2.7 mm/day (premonsoon) to 4.2 mm/day (postmonsoon) in the graminoid community. AET was greater than PET by 2.6 (premonsoon dry period) to 3.4 fold (postmonsoon dry period) (Table 3).

4.3.3. 2002 Growing Season

[31] Volumetric soil-water measurements started on April 9, 2002 and ended on September 24, 2002. The pre-monsoon dry period lasted from April 9, 2002, to July 3, 2002, an 85-day period (Figure 4). The post-monsoon dry period lasted 12 days from September 12, 2002, to September 24, 2002 because of heavy rains in late September.

[32] In 2002, treatment, community, and the treatment x community interaction were significant sources of variation in θ (Table 2). The graminoid community (Figure 4b) reduced θ more than the fern-graminoid community (Figure 4a) at both dry periods. There was a 71% reduction in θ between clipped and unclipped graminoid plots at the end of the premonsoon dry-down period versus 66% for the fern-graminoid community. In the postmonsoon season dry period in 2002, there was a 30% reduction in θ in the graminoid community versus 4% for the fern-graminoid community.

[33] Transpiration in the fern-graminoid community was 56 mm over the 85-day pre-monsoon period in 2002 producing a T rate of 0.66 mm/day (Table 3). The T rate for the 12-day post-monsoon period was similar at 0.63 mm/day (Table 3). E rates in 2002 in the fern-

Table 2. Results From MANOVA on θ (0–30 cm) for the 2000, 2001, and 2002 Growing Seasons[a]

Year	Sources of Variation	Degrees of Freedom	F Ratio	p[1]
2000	Community	1	5.8505	**0.0324**
	Treatment	1	41.0607	**0.008**
	Block	4	0.4141	0.7954
	Community x Treatment	1	0.3575	0.561
2001	Community	1	9.633	**0.0091**
	Treatment	1	62.3856	**<0.0001**
	Block	4	0.3771	0.8207
	Community x Treatment	1	9.8814	**0.0085**
2002	Community	1	10.3036	**0.0075**
	Treatment	1	102.8459	**<0.0001**
	Block	4	1.3586	0.3052
	Community x Treatment	1	23.258	**0.0004**

[a] Significant sources of variation are bolded.

Table 3. Mean Evaporation (E) and Transpiration (T) Totals and Rates, Actual Evapotranspiration (AET), Potential Evapotranspiration Calculated With the *Hamon* [1963] Method (PET), the Ratio of Actual to Potential Evapotranspiration (AET/PET), the Ratio of Transpiration to Potential Evapotranspiration (T/PET), and Vapor-Pressure Deficit (VPD) of Fern-Graminoid (FG) and Graminoid (G) Communities for Dry-Down Periods in the Premonsoon and Postmonsoon Seasons of Years 2000, 2001, and 2002[a]

Community-Year	Season	E, mm	T, mm	E Rate, mm/d	T Rate, mm/d	AET Rate, mm/d	PET Rate, mm/d	AET/PET	T/PET	VPD, kPa
FG-2000	Pre	48	90	1.3	2.4	3.7	2.6	1.4	0.92	2.2
	Post	80	62	4.0	3.1	7.1	2.5	2.8	1.2	2.0
FG-2001	Pre	46	126	1.2	3.3	4.5	2.6	1.7	1.3	2.2
	Post	174	47	6.2	1.7	7.9	2.7	2.9	0.70	1.9
FG-2002	Pre	100	56	1.2	0.66	1.9	2.3	0.8	0.29	2.0
	Post	77	7.5	6.4	0.63	7.0	2.0	3.5	0.32	1.6
G-2000	Pre	100	21	2.7	0.57	3.2	2.6	1.2	0.22	2.2
	Post	60	113	3.0	5.7	8.7	2.5	3.5	2.3	2.0
G-2001	Pre	103	157	2.7	4.1	6.8	2.6	2.6	1.6	2.2
	Post	120	140	4.2	5.0	9.2	2.7	3.4	1.8	1.9
G-2002	Pre	94	97	1.1	1.1	2.2	2.3	1.0	0.48	2.0
	Post	28	76	2.3	6.3	8.6	2.0	4.3	3.2	1.6

[a] Total water-year (October–September) precipitation was 293 mm in 2000, 440 mm in 2001, and 206 mm in 2002.

graminoid community were between 1.2 mm/day (premonsoon) and 6.4 mm/day (postmonsoon). PET estimated with the Hamon method in both communities was 2.3 mm/d for the premonsoon and 2.0 mm/d for the postmonsoon dry periods (Table 3). AET was 80% of PET in the premonsoon dry period, but was 3.5 fold higher in the postmonsoon dry period (Table 3).

[34] The graminoid community transpired 97 mm of water during the 85-day pre-monsoon period in 2002, producing a rate of 1.1 mm/day (Table 3). The T rate of the graminoid community was higher in the 12-day postmonsoon season (6.3 mm/day) than the premonsoon dry period (Table 3). E rates ranged from 1.1 mm/day (premonsoon) to 2.3 mm/day (postmonsoon). AET was equal to PET in the premonsoon dry period, but was 4.3 fold higher in the postmonsoon dry period (Table 3).

4.3.4. Environmental Conditions

[35] Correlations between mean daytime VPD and T or ET were calculated for each community using data polled over years and dry-down periods ($n = 6$). For the fern-graminoid community, VPD was not correlated with T ($r = 0.70$, $p = 0.12$), or ET ($r = -0.52$, $p = 0.31$). Similarly, VPD was not correlated with T ($r = -0.64$, $p = 0.17$), or ET ($r = -0.50$, $p = 0.31$) for the graminoid community.

4.4. Herbaceous Biomass

[36] Significant sources of variation in end-of-season herbaceous biomass were herbaceous community ($p < 0.0001$) and the community x year interaction ($p = 0.0328$). Biomass for the fern-graminoid community was significantly greater than biomass in the graminoid community in 2000 and 2001, with similar biomass in 2002 (Table 4). Biomass in the fern-graminoid community decreased in 2002 compared with 2000 and 2001, whereas biomass in the graminoid community did not change significantly over all years (Table 4).

5. Discussion

[37] The technique used to estimate ET and its components in our study during dry-down periods assumed that all changes to soil water in the rooting zone of the plant community were attributed to E or T rather than inputs or outputs of water from other sources. The use of distinct dry-down periods having no precipitation eliminated effects of direct inputs of water from recent precipitation. Another possible input or output of water into the rooting zone of the plants was water flow below the soil, but it is unlikely that there was enough capillary rise in these cobbly loam soils to draw water up from a water table which was generally >1.4 m deep. Although we did not measure drainage directly, we estimated that drainage may have been significant (>0.5 mm/d) when $\theta > 0.28$, or approximately greater than the field capacity of the soils. Our use of clipped plots in which all vegetation was removed allowed estimation of T from the difference in θ between clipped and unclipped plots at the end of each dry period, and estimation of E from temporal changes in θ during dry periods in the clipped plots. θ was often similar between clipped and non-clipped plots after recharge of soil water by snowmelt in the spring or by monsoon rains. This finding suggests that clipping did not strongly influence water infiltration into the soil. One limitation of this technique is that estimates of ET during periods of frequent precipitation or high antecedent soil moisture, such as the monsoon season or wet winters in our study, require accurate data on inputs of water from precipitation, and inputs and outputs from surface and subsurface water flow. Our study lacks this data, and thus our estimates of ET and its components are limited to the premonsoon (late April to late June) and postmonsoon (late August to late September) dry periods in each year.

[38] Our estimates of ET from changes in θ are the most accurate during dry-down periods when $\theta <$ field capacity because saturated drainage can be assumed to be minimal. Two such dry-down periods occurred in our study, the premonsoon periods of 2000 and 2002. Our estimates of actual ET (AET) based on changes in θ for these periods are similar to PET estimated for the same periods with the Hamon method, with AET/PET ratios that ranged between 0.8 and 1.4 (Table 3). T rates for these periods ranged between 0.66 and 2.4 mm/d for the fern-graminoid community, and between 0.57 and 1.1 mm/day for the graminoid community (Table 3). Dry-down periods that included conditions when $\theta >$ field capacity (postmonsoon seasons all

Table 4. End of Growing Season Aboveground Vegetation Biomass for Fern-Graminoid and Graminoid Communities in Years 2000, 2001, and 2002 (n = 5)[a]

Community	Year	Mass, g/m^2	Standard Error
Fern-graminoid	2000	899.7bc	36.6
	2001	1176c	160.
	2002	594.1ab	37.7
Graminoid	2000	326.9a	31.2
	2001	324.3a	31.8
	2002	465.9a	33.6

[a] Average mass values followed by the same letter do not differ significantly ($p < 0.05$) using Duncan's New Multiple Range Test.

years, premonsoon season 2001) occasionally produced higher estimates of T, and AET/PET ratios greater than 1.4. During dry-down periods when $\theta <$ field capacity, AET/PET ratios were between 0.8 and 1.4. Although we did not measure drainage, it is likely all AET/PET ratios >1.4 are influenced by gravity drainage. These estimates of T are likely overestimates because some of the soil water assumed to be transpired or evaporated actually drained below the plant roots and the depth of our 30 cm probes.

[39] Overall, T and ET were not significantly correlated with changes in mean daytime VPD for the six dry-down periods for both communities. The analyses were limited by the narrow range of mean daytime VPD (1.6 to 2.2 kPa) (Table 3), limited sample size (n = 6 dry-down periods), and the lack of daily E and ET values.

[40] Transpiration by herbaceous plants at Hart Prairie was an important component of site water balance in years 2000, 2001, and 2002 as shown by greater θ in the upper 30 cm of soil in clipped compared with unclipped plots. An important role of herbaceous transpiration on site water balance similar to our results has been reported for prairie vegetation in Colorado [*Dodd et al.*, 1998] and eastern Washington [*Gee et al.*, 1994]. The years included in our study were extremely dry (2002), moderately dry (2000), and slightly dry (2001) compared to long-term average precipitation, thus our results cannot be applied to wet years without further study.

[41] The daily ET rates of fern-graminoid and graminoid communities at Hart Prairie estimated from differences in soil θ (1.9 to 9.2 mm/d, depending on year, community and season) are within the range of ET estimates from studies of other vegetation communities in the western United States. *Raghuwanshi and Wallender* [2000] estimated daily ET rates of a grass reference crop in Davis, California, to range between 3 mm/d and 12 mm/d. The higher ET rates reported by *Raghuwanshi and Wallender* [2000] compared with our study are likely the result of the lower elevation (17 versus 2600 m asl) and higher mean annual air temperature at their study site. *Scott et al.* [2000] reported daily ET rates for a mesquite (*Prosopis sp.*) stand in southern Arizona during the growing season to vary between 1.0 and 2.4 mm/d. ET rate in a young ponderosa pine stand in the Sierra Nevada Mountains, California, estimated from eddy covariance data and the biophysical model, FORFLUX, ranged between 1 and 5 mm/d depending on measurement date [*Kurpius et al.*, 2003].

[42] Evaporation was an important component of ET in our study, especially in the fern-graminoid community where E rate exceeded T rate in four of the six combinations of measurement year and season. In contrast, E was a less important component of ET in the graminoid community; E rate was greater than T rate in only one of six combinations of year and season. However, E rate was at least 35% of T rate in the graminoid community for all measurement periods. Our finding of high E relative to T is consistent with other studies in the southwestern United States. For example, E and T rates were similar in a young ponderosa pine stand in the Sierra Nevada Mountains, California, in summer and fall when water stress limited plant transpiration [*Kurpius et al.*, 2003]. In contrast to these results, *Black and Kelliher* [1989] estimated only a 10% loss of soil water from E in a wetter ecosystem, a Douglas-fir forest with an understory of salal (*Gaultheria shallon*) in British Columbia, Canada. Intense solar radiation, low humidity, and low leaf area compared to a forest help explain the high E rates in our study in the high-elevation meadows of Hart Prairie.

[43] Biomass production of the two herbaceous communities was not clearly related to T rates. Biomass of the fern-graminoid community was greater than biomass of the graminoid community in every year. Differences were greatest in 2001, the wettest year (fern-graminoid 263% > graminoid), and lowest in 2002, the driest year (fern-graminoid 28% > graminoid) (Table 4). Despite higher biomass in the fern-graminoid community, T rate was 20 to 90% lower in this community compared with the graminoid community in five of six combinations of year and season. This finding suggests pronounced differences between communities in physiological, morphological, or environmental factors that influence T rate. For example, higher T rate of the graminoid community may have resulted from higher canopy conductance to water vapor, a higher proportion of plant biomass in leaf area, lower water use efficiency, greater penetration of solar radiation into the canopy, or deeper, more expansive roots compared with the fern-graminoid community.

[44] Comparisons between the slightly dry year of 2001 and the extreme drought year of 2002 suggest large differences in drought tolerance between herbaceous communities at Hart Prairie. In the fern-graminoid community, the decrease in biomass from 2001 to 2002 (−49%) was similar to the decrease in water year precipitation (−54%). In contrast, biomass of the graminoid community increased between these years by 44%. Effects of the 2002 drought on T rate depended on measurement season. In the pre-monsoon season when effects of the 2002 drought on θ were most severe, T rate decreased about the same between 2001 and 2002 in both communities (−80% fern-graminoid, −73% graminoid). In contrast, in the post-monsoon season, T rate decreased from 2001 to 2002 by 63% in the fern-graminoid community compared with an increase of 26% in the graminoid community. These results suggest that frequent severe droughts predicted in some climate change scenarios for the southwest United States [*Gregory et al.*, 1997; *Hanson and Weltzin*, 2000; *Rosenberg et al.*, 2003] will reduce growth and transpiration at Hart Prairie more in the fern-graminoid community than the graminoid community which contains a greater dominance by species with the C4 photosynthetic pathway.

[45] We hypothesized that T rate would be greater for pines that are encroaching into Hart Prairie than the herbaceous communities based on previous watershed studies of

woody plant encroachment into grasslands [*Bosch and Hewlett*, 1982; *Zhang et al.*, 2001]. The T rate of a low density stand (average density of 16 trees/ha) of ponderosa and limber pines that have encroached into Hart Prairie upslope of our study site based on sapflux data scaled to the entire stand was estimated to range between 0.06 to 0.24 mm/day for a 60-day growing season in 2000 [*Fischer*, 2001; *Fischer et al.*, 2002]. These rates are much lower than the T rates of the fern-graminoid (2.4 to 3.1 mm/d) and graminoid (0.57 and 5.7 mm/d) communities in our study in 2000. Thus, our results strongly refute our original hypothesis, and suggest that herbaceous communities use more water during the growing season than the scattered trees that have encroached into the Prairie. This finding suggests that thinning of the encroaching trees will have little effect on the water balance of Hart Prairie.

6. Conclusions

[46] The purpose of our study was to evaluate the potential role of herbaceous transpiration in limiting water that supports seed germination and seedling survival of the Bebb willow trees that grow in Hart Prairie, Arizona. Bebb willow seed germination is promoted by dispersal to moist soil [*Waring*, 1992a, 1992b; *DeWald et al.*, 1998; *DeWald and Springer*, 2001]. In every year of our study, seed dispersal of Bebb willows occurred in June when θ was the lowest during the growing season. Soil θ was higher in clipped plots compared with unclipped plots in June in every year and community. These results suggest that control of herbaceous vegetation might be effective in promoting regeneration of Bebb willow. Such control might occur in small plots in the immediate vicinity of sexually mature Bebb willows to provide areas of moist soil with little herbaceous competition to promote seedling establishment. Vegetation management that decreases T of herbaceous vegetation upslope of Bebb willow stands should allow more recharge into shallow aquifers that support the willows. Future research should address the type of management (e.g., burning, grazing) that would be effective in reducing T of herbaceous communities as well as being socially acceptable.

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