Soil Water and Vegetation Responses to Precipitation and Changes in Depth to Ground Water in Owens Valley, California

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Prepared in cooperation
with Inyo County and the
Los Angeles Department
of Water and Power

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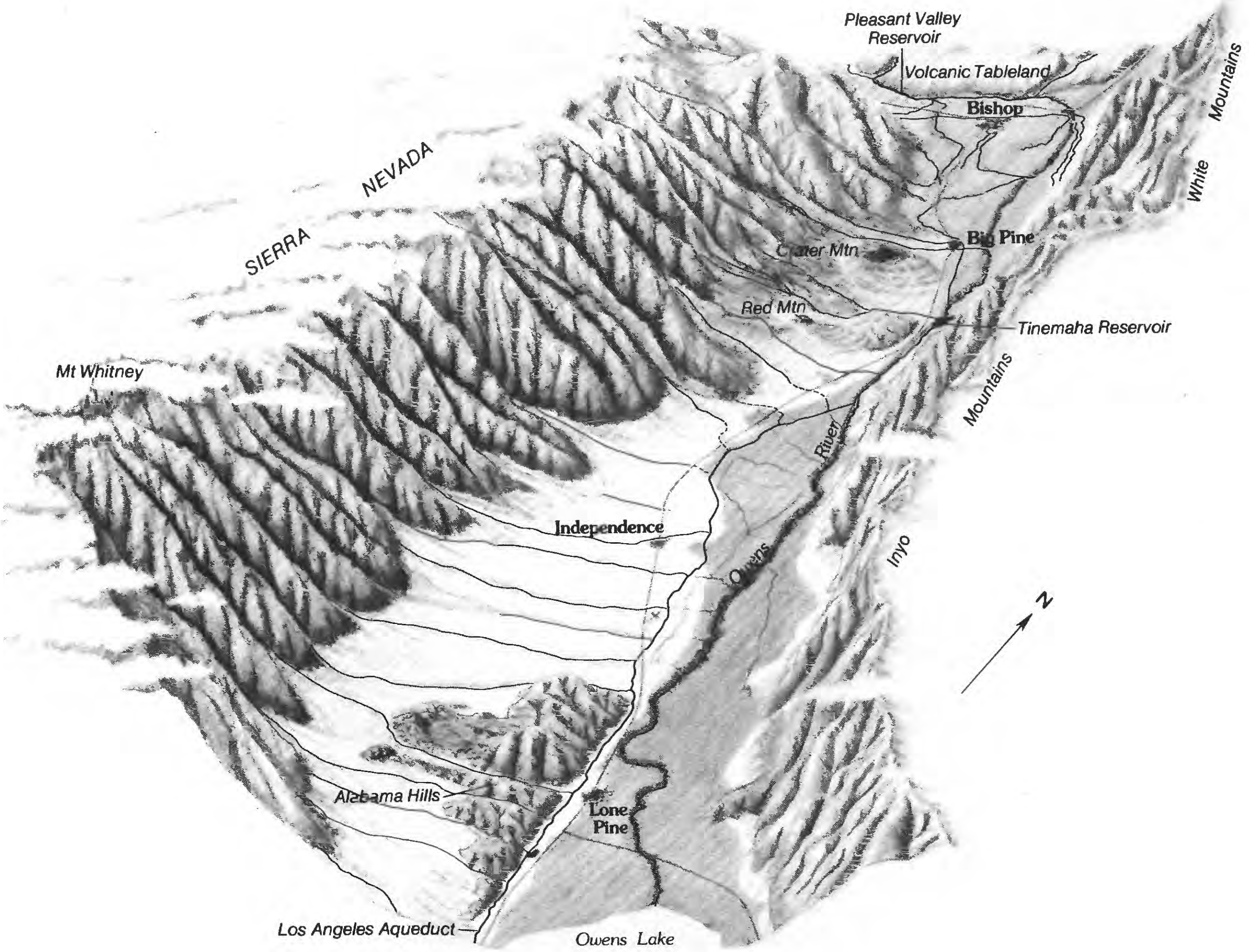
SOIL WATER AND VEGETATION RESPONSES TO PRECIPITATION AND CHANGES IN DEPTH TO GROUND WATER IN OWENS VALLEY, CALIFORNIA



Vertically exaggerated perspective and oblique view of Owens Valley, California, showing the dramatic change in topographic relief between the valley and surrounding mountains.

Chapter G

Soil Water and Vegetation Responses to Precipitation and Changes in Depth to Ground Water in Owens Valley, California

By STEPHEN K. SORENSON, PETER D. DILEANIS, and
FARREL A. BRANSON

Prepared in cooperation with
Inyo County and the
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U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2370

HYDROLOGY AND SOIL-WATER-PLANT RELATIONS IN OWENS VALLEY, CALIFORNIA

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

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FRONTISPIECE

Perspective and oblique view of Owens Valley, California, showing the dramatic change in topographic relief between the valley and surrounding mountains.

FIGURES

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SYMBOLS USED IN TEXT

θ	Soil water content
θ_v	Volumetric soil water content
ψ_m	Matric potential
ψ_π	Osmotic potential

CONVERSION FACTORS

For readers who wish to convert from the metric system of units to the inch-pound system of units, the conversion factors are listed below.

Multiply	By	To obtain
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
millimeter (mm)	0.03937	inch
centimeter (cm)	0.3937	inch
liter (L)	0.2642	gallon
liter per second (L/s)	15.85	gallon per minute
kilopascal (kPa)	0.1450	pound per square inch
megapascal (MPa)	145.04	pound per square inch

Temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following equation:

$$°F=1.8(°C)+32.$$

Sea Level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Soil Water and Vegetation Responses to Precipitation and Changes in Depth to Ground Water in Owens Valley, California

By Stephen K. Sorenson, Peter D. Dileanis, *and* Farrel A. Branson

Abstract

Vegetation on the floor of Owens Valley, California, is composed predominantly of phreatophytic desert communities that are adapted to small quantities of precipitation and alkaline soils. These plant communities are believed to be dependent on the continuing presence of a shallow water table. Maintaining existing plant communities is important to preserve the environmental quality of the valley. Proposals to pump additional quantities of ground water from the valley for export to the city of Los Angeles caused concern about the effect of pumping on the existing vegetation and how the plants would adapt to short- or long-term declines of the shallow water table.

To test the ability of selected major shrub species to adapt to water-table decline, four sites were selected, pump-equipped wells were installed, and water-table drawdown was monitored. Soil samples were collected with a hand auger and analyzed by using the filter-paper method to monitor changes in soil water content and soil matric potential at test sites. Plant reactions were determined by measurements of plant cover, shoot growth, and xylem pressure potential.

Results of 3 years of monitoring show that growth and cover repetition of the shrubs studied are affected greatly by the quantity of annual precipitation, especially at sites with coarse-textured soils. Plants were not affected by drying soil in the root zone until the maximum matric potential exceeded 4.3 pF (–1,950 kilopascal) at depths greater than 0.5 meter. Rabbitbrush was most sensitive to dry soil and was the only shrub species that died as the result of water stress from water-table drawdown. The change in cover repetition correlated positively with the magnitude of water-table drawdown at one site and negatively at another site. Measurements of xylem pressure potential taken before dawn correlated well with water content in the upper 1.5 meters of soil.

The magnitude of water-table drawdown achieved by the pump-equipped wells was less than expected at three of the four sites. Additional water-table drawdown for a longer period of time would be needed to separate the effects of water-table drawdown from the effects caused by differences in soil textures and natural fluctuations in the quantity of precipitation.

INTRODUCTION

The export of water from Owens Valley, California, since 1913 has caused major changes in land and water use and, consequently, a change in vegetation communities. Much of the existing vegetation consists of desert shrubs and grasses which are, to a great extent, drought tolerant but whose long-term existence on the valley floor depends on soil water derived from the shallow water table that underlies much of the valley. Proposals to pump additional quantities of ground water from the valley have caused concern that the resulting pumping will decrease this needed source of soil water and, therefore, decrease the quantity of existing phreatophytic vegetation communities.

Greater than average ground-water pumping for in-valley uses and export to the city of Los Angeles during the 1970's, which included two consecutive years of low rainfall, may have caused the loss of much of the phreatophytic vegetation around some of the major well fields. Although increased ground-water pumping and loss of phreatophytic vegetation seem to be correlated, little is known about the tolerance of these plants to water-table drawdown. The fundamental questions of plants' survival need to be considered, specifically, the magnitude and duration of water-table drawdown they could withstand, as well as the effects of chronic or severe water stress. Answers to these questions can provide the basis for a rational water-management plan for Owens Valley that will allow the pumping of needed water while minimizing environmental effects to the valley.

In 1982 the U.S. Geological Survey, in cooperation with Inyo County and the Los Angeles Department of Water and Power, began a series of comprehensive stud-

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ies to define the ground-water system in Owens Valley and to determine what effect ground-water withdrawals might have on native vegetation. These studies, termed the Owens Valley ground-water and plant-survivability studies, are discussed more fully by Hollett (1987) and Danskin (1988). The results of the individual studies, as well as a comprehensive summary, are presented in a Water-Supply Paper series as the interpretive products of the studies become available. The series consists of eight chapters as follows:

A. A summary of the hydrologic system and soil-water-plant relations in Owens Valley, California, 1982–87, with an evaluation of management alternatives.

B. Geology and water resources of Owens Valley, California.

C. Estimating soil matric potential in Owens Valley, California.

D. Osmotic potential and projected drought tolerances of four phreatophytic shrub species in Owens Valley, California.

E. Estimates of evapotranspiration in alkaline scrub and meadow communities of Owens Valley, California, using the Bowen-ratio, eddy-correlation, and Penman-combination methods.

F. Influence of changes in soil water and depth to ground water on transpiration and canopy of alkaline scrub communities in Owens Valley, California.

G. Soil water and vegetation responses to precipitation and changes in depth to ground water in Owens Valley, California (this report).

H. Numerical evaluation of the hydrologic system and selected water-management alternatives in Owens Valley, California.

Purpose and Scope

The purpose of this report is (1) to describe variations in soil water content (θ) and soil ψ_m (matric potential) caused by changes in precipitation and depth to ground water, and (2) to describe the physiological responses of selected shrub species caused by changes in precipitation and depth to ground water.

The study focused on high ground water alkaline scrub communities dominated by phreatophytic shrubs. These communities were selected because of their wide distribution on the valley floor, their proximity to potential ground-water pumping sites, and their suspected dependence on shallow ground water.

Soil water content and soil matric potential were determined periodically throughout the growing seasons from the surface to near the water table. Physiological effects on the plants were inferred from measurements of plant growth, xylem pressure potential, and cover density. These data were collected at a total of fifteen 38-m transects at four sites in Owens Valley. Wells equipped with pumps were installed at each of the four sites in order to cause a specific quantity of water-table drawdown.

Background

Much of the floor of Owens Valley is covered by phreatophytic shrubs and grasses. The term "phreatophyte" came into common usage with the 1927 publication of Meinzer's classic paper titled, "Plants as indicators of ground water." Meinzer (1927) defined a phreatophyte as a plant that "feeds on ground water" by extending its roots down to the water table or to the capillary zone above the water table. Phreatophytes have received considerable attention from the scientific community since that time, with most of the studies aimed at decreasing the quantity of ground water that is transpired by these plants. In many areas of the desert Southwest, phreatophytes transpire large quantities of water that are considered to be "consumptive waste" (Robinson, 1958) because ground water passes to the atmosphere without human use. Much of the work associated with control of phreatophytes has involved the study of, and attempts to eradicate, saltcedar (*Tamarix chinensis*). This plant, introduced to the Southwest in the late 1800's, now covers extensive areas of flood plain. Other phreatophytes grow in shallow ground-water areas throughout the desert Southwest and cause what Robinson (1958) referred to as the "phreatophyte problem." This narrow view of phreatophytes as pipelines to the water table, resulting in large quantities of wasted water with no benefit to humans, ignores the beneficial uses of these plants. Phreatophytic vegetation provides habitat for wildlife, provides recreational opportunities for humans, and stabilizes soil, thus reducing soil loss and air pollution from windblown dust. In Owens Valley, these beneficial uses and the desirability of retaining phreatophytic plants are recognized. Vegetation is important not only to the local residents but also to visitors who create the area's most important economic base, tourism.

In the early 1900's, planners for the rapidly growing city of Los Angeles saw Owens Valley as a long-term, plentiful supply of water. The city purchased most of the valley floor in Owens Valley, and in 1913 an aqueduct was completed that diverted surface water from Owens Valley to Los Angeles. In addition, a series of wells were constructed in the 1920's to supply ground water to the aqueduct during periods of low surface-water runoff. A second aqueduct, completed in 1970, increased the quantity of water that can be diverted. Much of the additional diversion comes from the Mono Lake basin to the north of Owens Valley.

Diversion of surface and ground water from Owens Valley has caused numerous conflicts over the years between the city of Los Angeles and the residents of Inyo County (Smith, 1978). A central focus of recent conflicts is the effect of surface- or ground-water diversions on the native vegetation on the valley floor. There is concern that lowering of water tables caused by pumping, or by diversion of surface water that would otherwise recharge ground water, could kill or decrease productivity of existing vegetation and cause a decrease in vegetative cover in plant communities that require a shallow water table.

Description of Study Area

Owens Valley lies between the Sierra Nevada and the White and Inyo Mountains (fig. 1). The valley floor is about 190 km long and ranges in altitude from about 1,100 to 1,250 m. Mountains along the east and west sides of the valley rise 900 to 3,050 m from the valley floor (fig. 2). Owens Valley is in the rain shadow east of the Sierra Nevada. Despite little precipitation, ground water is plentiful in the valley. Water from streams that are fed by the Sierra Nevada snowpack percolates through the unconsolidated alluvial deposits along the western valley margin and supplies most of the recharge to the ground-water system. The natural water table across much of the valley floor ranges from land surface to about 4 m below land surface. In these areas, ground water is within the reach of roots of phreatophytic shrubs and grasses that make up much of the valley floor plant communities (R.H. Rawson, Los Angeles Department of Water and Power, written commun., 1986).

Soils in the Bishop Basin (north of Tinemaha Reservoir) (Hollett and others, 1991) generally are sandy but also contain lenses of finer loams, silts, and clays. Soils in the Owens Lake Basin (south of Tinemaha Reservoir) are mostly silty clays and silty clay loams but contain lenses of fine to coarse sand at some depths. Although the soils are derived from alluvial materials, soil textures are variable throughout the valley floor and are affected by the source of materials, by sorting action of stream velocities at time of deposition, and by the presence of lake deposits, particularly in the Owens Lake Basin. Thus, alternating coarse- and fine-textured layers are characteristic of most valley floor soils.

The rain-shadow effect of the Sierra Nevada to the west causes the climate of the Owens Valley to be arid. Annual precipitation at Bishop and Independence averaged 142 and 137 mm, respectively, between 1951 and 1980 (National Oceanic and Atmospheric Administration, 1982). Most precipitation occurs from October through February. Maximum and minimum temperatures for Bishop are 43 and −26 °C. At Independence, the temperature extremes are 43 and −21 °C. The growing season (frost-free days) is 152 days at Bishop and 200 days at Independence.

Plant Communities

Most of the natural vegetation on the floor of Owens Valley has been described in one of four community assemblages (Griepentrog and Groeneveld, 1981). The distribution of these plant communities depends largely on the physical and chemical (salinity) characteristics of the soil and on the availability of water. The four plant communities (fig. 3) and their characteristic plant species are as follows:

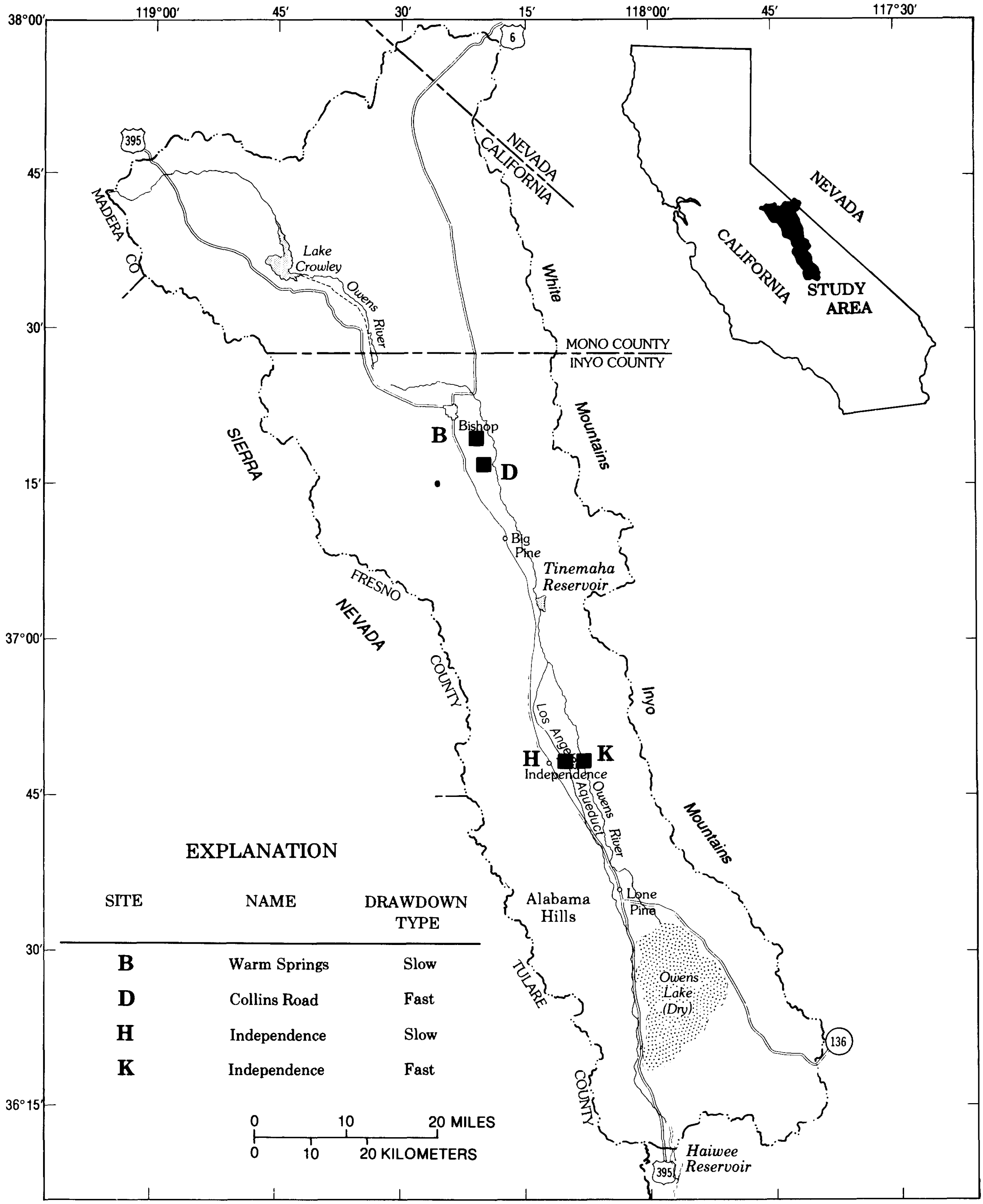
1. High ground water alkaline meadow (saltgrass meadow) (fig. 3*A*) is highly salt tolerant and grows in areas where the water table ranges from land surface to 1.5 m below land surface most of the year. Characteristic plant species are:

Species name	Common name
Distichlis spicata	saltgrass
Glycyrrhiza lepidota	wild licorice
Juncus balticus	wire rush
Sida leprosa	alkali mallow
Sporobolus airoides	alkali sacaton

2. High ground water alkaline scrub (greasewood, Nevada saltbush scrub) (fig. 3*B*) is highly tolerant of alkalinity and salinity. This community is common to areas where water tables range from 1 to 3 m below land surface. The predominant plant species are phreatophytic and require contact between the rooting zone and the water table. These communities contain additional plant species characteristic of the high ground water alkaline meadow community. Characteristic plant species are:

Species name	Common name
Atriplex torreyi	Nevada saltbush
Chrysothamnus nauseosus	rabbitbrush
Sarcobatus vermiculatus	greasewood
Suaeda torreyana	inkweed

3. Dryland alkaline scrub (shadscale scrub) (fig. 3*C*) is in areas where there is no connection between the water table and the rooting zone. This community is in soils that are well drained and usually alkaline or saline. Characteristic plant species are:



EXPLANATION

SITE	NAME	DRAWDOWN TYPE
B	Warm Springs	Slow
D	Collins Road	Fast
H	Independence	Slow
K	Independence	Fast

Figure 1. Location of study area and water-table drawdown sites.

Species name	Common name
Ambrosia dumosa	burrobush
Artemisia spinescens	bud sage
Atriplex confertifolia	shadscale
Atriplex polycarpa	allscale
Ceratoides lanata	winterfat
Hymenoclea salsola	cheesebush
Lycium cooperi	peach thorn
Psorothamnus sp.	dalea
Stephanomeria pauciflora	desert milk-aster

4. Dryland nonalkaline scrub (sagebrush scrub) (fig. 3*D*) is on well-drained coarse soils, generally on the alluvial fans that border the valley. This vegetation generally is intolerant of high alkalinity or salinity. Characteristic plant species are:

Species name	Common name
Artemisia tridentata	big sagebrush
Chrysothamnus teretifolius	green rabbitbrush
Ephedra nevadensis	Nevada squawtea
Eriogonum fasciculatum	California buckwheat
Purshia glandulosa	desert bitterbrush

Many variations of these basic communities exist in different parts of the valley. For instance, shadscale and big sagebrush commonly grow in conjunction with the high ground water alkaline scrub community in the northern parts of the valley, where water tables are deeper than 3 m and soils are coarse grained and less alkaline. Sagebrush, in particular, commonly grows on raised sand-dune deposits. Most of the Owens Valley floor is covered with one of these basic plant communities. The remainder of the valley floor is occupied by irrigated agriculture, urban areas, and riparian communities along the major stream courses.

STUDY DESIGN

For this study, two types of water-table drawdown sites were established in high ground water alkaline scrub communities to determine the ability of plants to survive when water tables are lowered. The first type of site was referred to as a fast-drawdown site. The goal was to produce a range of water-table depressions and associated water deficit stress in plants at a series of vegetation transects located at increasing distances from a cluster of pump-equipped wells. These wells were to produce about 9 m of drawdown near the pumped wells and correspondingly less at greater distances from the wells. The 9 m of drawdown was considered sufficient to rapidly eliminate the contact between the water table and the rooting zone of the phreatophytes.

The second type of study site was referred to as a slow-drawdown site. The goal was to produce consecutive shallow increments of water-table drawdown uni-

Figure 2. View looking southeast across southern Owens Valley. Inyo Mountains are on the left, with the town of Independence in the center of the valley; Sierra Nevada is on extreme right. Low hills in background are Alabama Hills, and thin white streak to their left is Owens Lake. (Photograph courtesy of M.L. Blevins, Los Angeles Department of Water and Power.)

formly throughout a localized area. The water table at the test sites was to be lowered in annual increments of about 2 m and the response of the plants studied to determine whether phreatophyte roots can follow a slowly declining water table. Some evidence indicates that this is a possibility with certain phreatophytes, such as greasewood, which may root as deeply as 18 m under certain conditions (Robinson, 1958).

A

B

Figure 3. Major plant communities in Owens Valley. *A*, High ground water alkaline meadow. *B*, High ground water alkaline scrub. *C*, Dryland alkaline scrub. *D*, Dryland nonalkaline scrub.

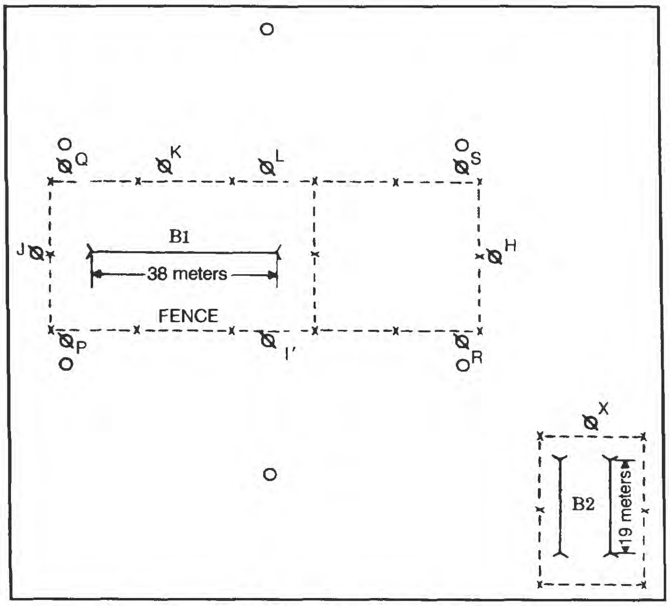
The criteria used to select the water-table drawdown sites included (1) vegetation representative of the Bishop and the Owens Lake Basins, (2) nearly uniform vegetation, (3) soils that could be hand augered, (4) no evidence of previous cultivation, (5) no evidence of geologic faulting, and (6) no evidence of previous irrigation or water spreading.

Two fast-drawdown sites were established: Site K about 5 km east of Independence and site D about 8 km southeast of Bishop (fig. 1). Two slow-drawdown sites

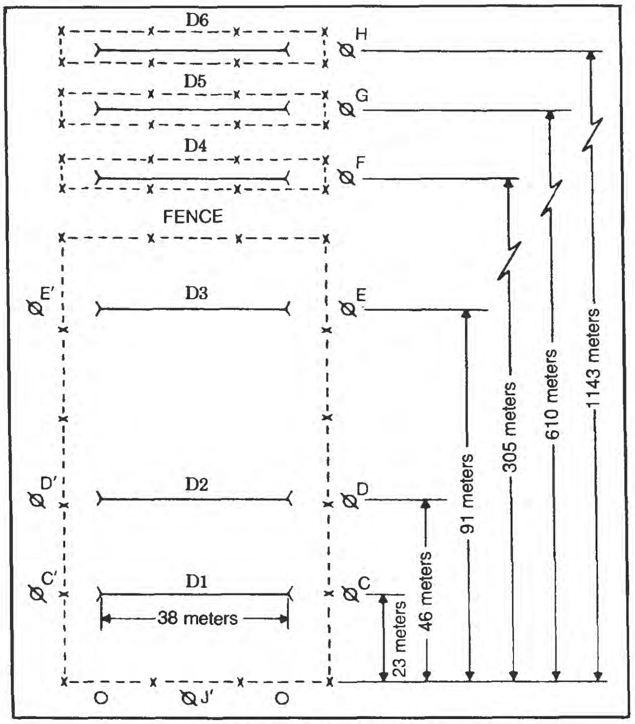
C

D

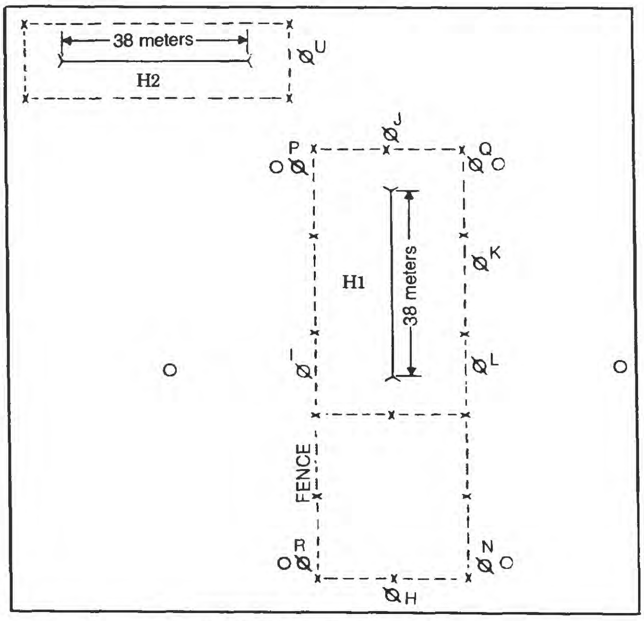
Figure 3. Continued.



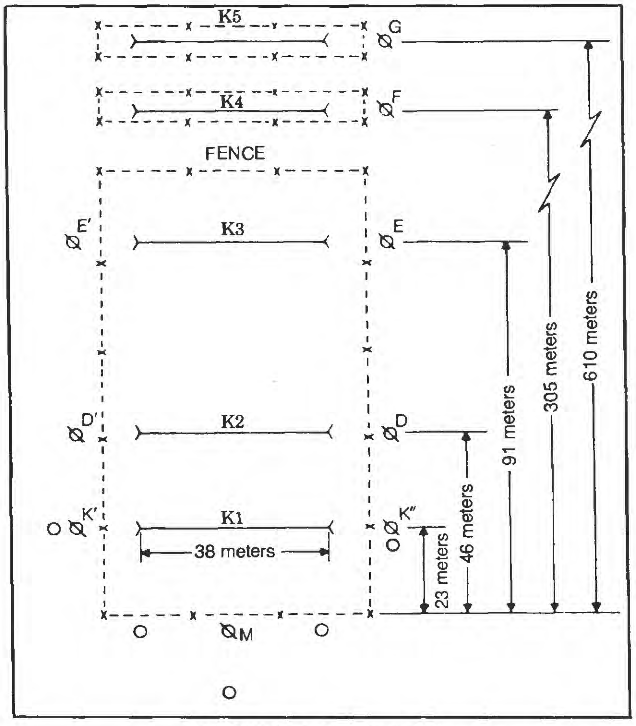
SITE B (slow-drawdown site)



SITE D (fast-drawdown site)



SITE H (slow-drawdown site)



SITE K (fast-drawdown site)

EXPLANATION

(No scale)

○ PUMP-EQUIPPED WELL

⌀ D MONITORING WELL

)—D2—(VEGETATION TRANSECT

Figure 4. Location of pump-equipped and monitoring wells for water-table drawdown sites. Letters identify individual wells.

also were established: Site H about 4 km east of Independence and Site B about 5 km southeast of Bishop (fig. 1). Diagrams of these sites show the location of the pump-equipped and water-level monitoring wells (fig. 4). Before drilling the pump-equipped wells at each location, test wells were drilled and equipped with temporary pumps to determine aquifer properties. Data from these pump tests indicated that four pump-equipped wells would be needed at site K, because of lower transmissivity, and two would be needed at site D. Computer simulations done by Los Angeles Department of Water and Power indicated that a cluster of six wells surrounding the slow-drawdown sites (sites H and B) would be needed to produce a uniform depth to water beneath the vegetation transects. Electrical power to the pumps was supplied by generators at sites D and B and by an electrical line extended from a nearby radio station at sites K and H. Fenced exclosures were established around all the sampling transects to prevent damage caused by cattle and elk.

Vegetation sampling transects 38 m long (fig. 4) were established at increasing distances from the pump-equipped wells at the fast-drawdown sites and near the center of the slow-drawdown sites. At the fast-drawdown sites, transects were established at distances of 23, 46, 91, 305, and 610 m from the wells. Because of the higher transmissivity at site D, an additional transect was established 1,143 m from the wells. This transect and the one at 610 m at site K were considered controls in that they were beyond the influence of the pump-equipped wells. At the slow-drawdown sites, exclosures were divided into two sections. A single vegetation transect was established in the larger section of each exclosure; the smaller section was used by Inyo County and Los Angeles Department of Water and Power for separate studies. Control exclosures were established near each slow-drawdown site to compare vegetation responses with those of the plants in the drawdown sites. All the water pumped from the wells was spread on the land some distance from the site or was pumped into an irrigation channel nearby. Monitoring wells for observation of water-table levels were installed using a jetting method at various locations around the fenced exclosures at the slow-drawdown sites and near one or both ends of each transect at the fast-drawdown sites. Depth to water in all observation wells was measured weekly during the study period. In addition, one monitoring well, 100 to 150 mm in diameter, at each site was equipped with a continuous water-level recorder.

METHODS

Soils were sampled for water content and matric potential near each vegetation transect monthly during 1984 and two to four times during the 1985 and 1986 growing seasons. Samples were obtained with a tubular auger 50 mm in diameter (Sorenson and others, 1989). Samples collected at each 0.1-m depth increment were retained for analysis. Each soil profile was sampled from the surface to near the water table. Each sample was emptied into a sealable polyethylene bag of 1.4 L capacity. A disk of standard filter paper (McQueen and Miller, 1968), previously treated to prevent decomposition by soil organisms, was inserted with each sample. Each bag was then sealed in a metal container with electricians' tape to prevent water evaporation. After transport to the laboratory, samples were stored for at least 7 days in an incubator at 20±0.1 °C to ensure moisture equilibrium between the soil and filter paper. The water content of the soil and the standard paper was determined gravimetrically. Soil and paper were dried in a forced-draft oven at 105 °C. The water content of soil and paper was calculated as grams of water per gram of oven-dried material. Soil matric potential at the time of sampling was determined from the water content of the filter papers using calibration curves (Sorenson and others, 1989).

Figure 5. Use of point-frame apparatus.

To measure changes in vegetative cover, 38-m linear transects were established in 1983, at least 1 year before pumping. Vegetative cover was measured using the point-quadrat method (Goodall, 1952). The point frame (fig. 5) holds a linear array of steel pins above the plant canopy and perpendicular to the ground. The surveyor lowers each pin to the ground while recording the number of contacts made of each plant species by the pointed end of the pin. The point frame was used to provide two kinds of measurements: (1) percentage cover, derived from the records of the first contact made by each pin, and (2) cover repetition, a measurement of foliage density defined by Goodall (1952) as the average number of layers of foliage covering each point of ground. Cover repetition is determined by counting the total number of pin contacts, measured as hits per 100 pins, made with each species as the pins are lowered to the ground through the plant canopy. Soil-surface features, such as rock, bare soil, and mulch, also were recorded. Pins were spaced at 152-mm intervals along the 38-m transects to yield 250 pin projections per transect. These measurements were made in September 1983 and 1984, and in May, July, and September 1985 and 1986.

The internal-water status of the test plants was measured using a pressure chamber (Scholander and others, 1965). This apparatus measures negative pressure potentials in the water-conducting xylem tissues. Xylem pressure potential was measured monthly during the growing season, both at predawn and midday, when water deficits were at their minimum and maximum, respectively.

Growth of the most common shrub species near each transect was measured at intervals varying from bimonthly to monthly. Color-coded electrical wire was put on three branches of each plant representative of the three or four most common shrub species at each transect. The growth of terminal and lateral branches distally from wires was measured.

At the time of each growth measurement, phenological stages for each species were recorded. Stages recorded were (0) dormant (spring), (1) beginning leaf, (2) one-half leaf, (3) three-fourths leaf, (4) full leaf, (5) flower stalks (buds) visible, (6) early bloom, (7) full bloom, (8) late bloom or early seed, (9) seed ripe, (10) seed shattering, and (11) dormant (autumn).

EVALUATION OF DRAWDOWN

The quantity and duration of water-table drawdown at the four test sites were critical to evaluation of the plants' reaction to the drawdown. The operation of each drawdown site will be discussed in detail to explain the amount and duration of the drawdown, as will the site design and the equipment's performance.

Site K

Site K (Independence fast-drawdown site) was the first test site completed and pumped. Pumping began on March 21, 1984, at wells A, B, C, and L (fig. 4). The average quantity of water pumped was different at each pump-equipped well because of differences in productivity. Well A was the most productive at about 4.4 L/s. All pump-equipped wells were pumped to their maximum capacity in an effort to obtain the maximum drawdown. (Hydrographs for selected monitoring wells at each drawdown site are shown in figure 6.) Depth to water near the pump-equipped wells was about 0.5 m below land surface at the start of pumping (fig. 6*A*).

The goal was 9 m of drawdown near the pump-equipped wells. Maximum drawdown from the water level at the start of pumping was only about 3.9 m at monitoring well K´´ (adjacent to transect K1). During most of the drawdown period, the drawdown averaged about 3.1 m. This resulted in a depth to water between about 4.2 and 4.7 m at transect K1. By contrast, depth to water near transect K5 (610 m from the pump-equipped wells) remained at about 2.0 m throughout the pumping. Because the initial prepumping water level was deeper at transect K5 than at K1, the difference in actual depth to water between transects K1 and K5 during the pumping period was a maximum of about 1.9 m. The reasons for the smaller than expected drawdown were (1) the low productivity of the wells, caused by lower than expected transmissivities in the formation, and (2) the existence of a large hydraulic head below confining clay layers at a depth of about 30 m throughout the area (Hollett and others, 1991). The pressure head in the 37-m-deep monitoring well P was about 9 m above land surface. Well P was pumped intermittently during 1986 in an attempt to reduce the pressure head of the deeper confined aquifer; however, this additional pumping did not result in substantial drawdown of the shallow unconfined aquifer. The extent of the hydraulic connection between the two aquifers at this site was not determined. Because of less than expected drawdown at the pump-equipped wells, there was correspondingly less drawdown at the transects along the cone of depression. Maximum drawdown at monitoring well E at transect K3, 91 m from the pump-equipped wells, was about 2.7 m (fig. 6*B*). Monitoring well G at transect K5, 610 m from the pump-equipped wells, was not affected significantly by drawdown from the pumped wells, as expected.

Because this site was equipped with electrical power from power lines, pumping was not interrupted significantly from the start of pumping until the pumps were stopped in November 1986. There were some pump failures, but the pumps were replaced rapidly enough that dewatering was not significantly affected at this site. The discharge line from pump-equipped well L leaked

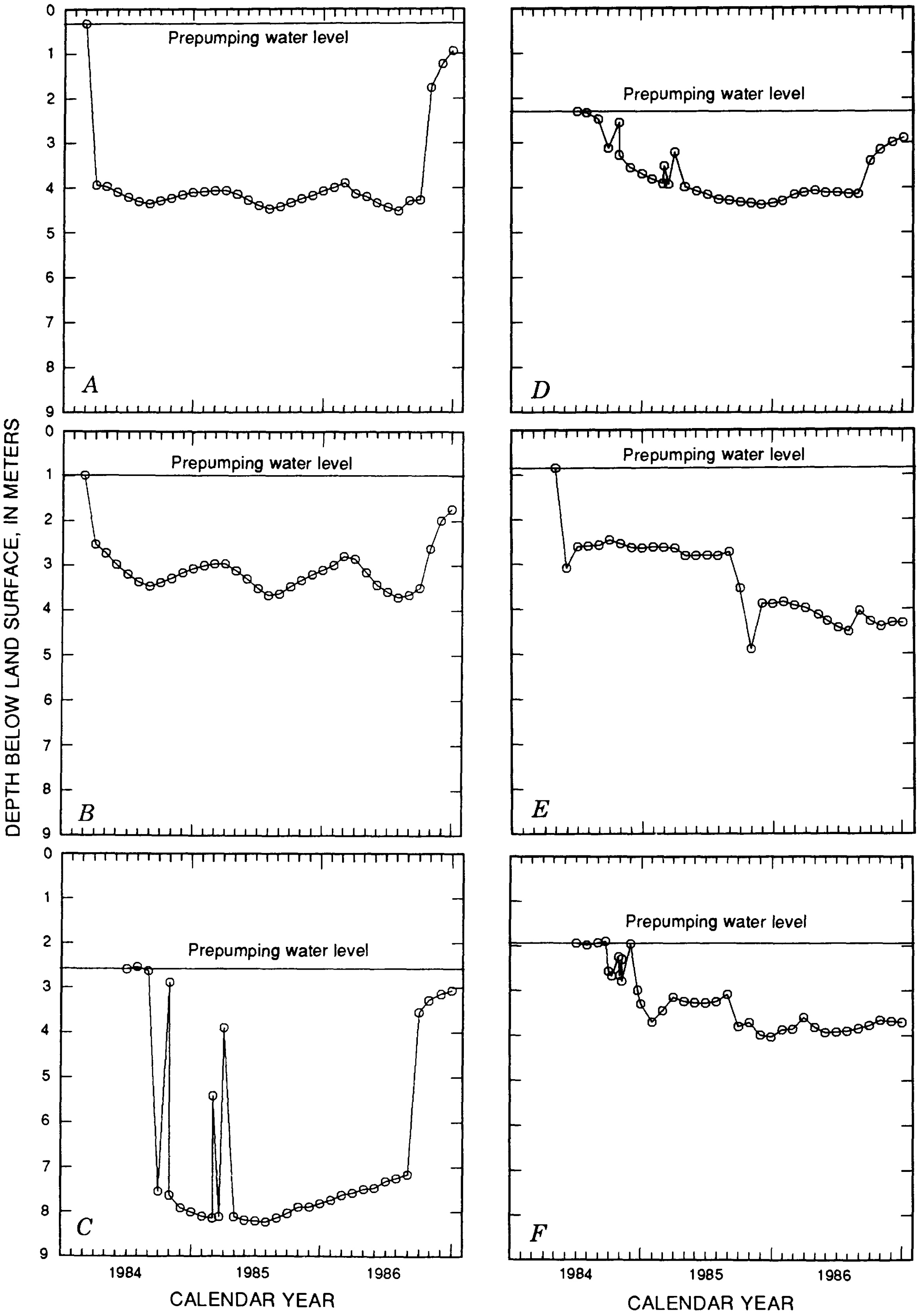


Figure 6. Ground-water levels at water-table drawdown sites. *A*, Site K, well M. *B*, Site K, well E. *C*, Site D, well J′. *D*, Site D, well F. *E*, Site H, well I. *F*, Site B, well L.

an unknown quantity of water into the exclosure at transect K1 for an unknown period of time in March 1986. Soil water increased significantly in the upper part of the soil along much of this transect.

Another factor related to the construction and operation of the drawdown sites K and H that probably had a significant effect on the reaction of the plants was that vegetation outside the fenced exclosures was cleared away for a distance of 3 to 9 m. In addition, sandy soil was brought to the site and spread on these cleared areas in an effort to decrease the windblown dust at the drawdown site. Lack of competition from plants in the cleared area and the additional water infiltrated into the added sandy layer increased the available water in the shallow rooting zones of the plants around the perimeter. The exclosure was large enough so that these perimeter effects apparently did not influence the plants near the center of the compound, but this is not certain.

Site D

Pumping at site D, the second fast-drawdown site, started in October 1984. This site was equipped with a generator to supply electrical power to the pumps. Numerous equipment problems (primarily generator failures) occurred during the first 2 months after pumping started. Well A was pumped at a rate of about 17 L/s and well B at about 7.6 L/s. This pumping resulted in a water-table drawdown at monitoring well J′ of about 5.5 m as of March 1985 (fig. 6*C*).

Equipment failure caused suspension of pumping for long periods during March and April 1985, and the water levels in monitoring well J′ recovered to within 1.5 m of prepumping water level. This was a setback to the study because the recharge of the drained soil profile occurred just before the time of year when the plants were using the maximum amount of soil water. By May 1985, the equipment problems were solved and, except for some power outages of a few hours' duration, the pumping continued until October 1986.

After initial drawdown, water levels at well J′ slowly increased because of a gradual decrease in the efficiency of the wells. The hydrograph for monitoring well F at transect D4 (fig. 6*D*) shows a pattern similar to that of well J′ (fig. 6*C*). Maximum drawdown at well F was about 1.8 m. The water tables at the control site (transect D6) varied within 0.3 m of the prepumping water level during the time the pumps were running.

Site H

Pumping at the slow-drawdown site near Independence (site H) began June 12, 1984. The initial goal at the site was to obtain about 1.8 m of drawdown the first summer. The hydrograph for monitoring well I (fig. 6*E*) shows that this goal was reached, and other monitoring wells around the compound indicated a nearly uniform water table beneath the fenced compound. Because pumping of all six pump-equipped wells initially drew the water table down beyond the 1.8 m goal, pumps on three wells were turned off until October 1985. Pumping was increased in October 1985 to implement the second phase of drawdown. The water table quickly declined an additional 1.2 m and continued to decline to near the goal of an additional 1.8 m by August 1986. Pumping was maximized at this point, but additional drawdown was not possible with the existing pumping system.

The prepumping water table was at or within 0.3 m of the surface in some of the lower-lying areas near the drawdown site. The control site established for comparison with this drawdown site (transect H2) was about 137 m from the pump-equipped wells. This site did not serve well as a control because the water table declined from less than 0.3 m when the pumping began to about 2.2 m by October 1986. The monitoring well drilled at this site was only 1.5 m deep and became dry within 2 months of the start of pumping. It is not certain if the water-table decline at this control site was due to test pumping or if it reflected an overall decline in water levels in the area from artificially high levels at the start of the test.

Site B

Pumping was started in the autumn of 1984 at the slow-drawdown site B near Bishop. This site, which was equipped with a generator to power the pumps, had numerous startup equipment problems that delayed consistent operation of the pumps until January 1985. This site was similar to the slow-drawdown site near Independence (site H) in that it had six pump-equipped wells around the perimeter of the exclosure (fig. 4). Through the 1985 growing season, 1.2 to 1.4 m of drawdown was obtained at monitoring well L at this test site instead of the objective of 1.8 m (fig. 6*F*). When the pumping was increased in late 1985 to produce the second increment of drawdown, the water table declined to a total drawdown of about 2.0 m. In an effort to produce additional drawdown, larger pumps and discharge lines were installed at all the pumps; however, these efforts failed to produce the desired drawdown. Equipment failures caused occasional, temporary rises in the water table of unknown amounts in the exclosure.

SOIL WATER RESPONSES

Soil is one of the critical factors that determine the type of vegetation found in any habitat. Plants rely on the soil, not only for physical support, but also for a supply of water and inorganic nutrients. Soils have characteristic physical properties that allow them to retain water. These characteristics are important to plants because the quantity of water retained in a soil and the availability of that water to the plant are critical factors for the plant's survival. In general, the most critical factors in soils relating to plants are soil water content (θ) and soil ψ_m (matric potential). Soil ψ_m (sometimes referred to as soil suction) is a measure of how strongly water is held by soil.

The relation between θ and soil ψ_m usually is referred to as a characteristic curve. A soil at saturation has virtually no soil suction or a soil ψ_m of zero. External forces such as gravity, applied to the soil, cause the water to drain starting with the larger void spaces. Most soils drain by gravity until soil ψ_m reaches about –10 to –20 kPa. Additional decreases in θ result in lower soil ψ_m.

In soils, water is removed primarily by extraction by plant roots or by evaporation at the surface. As water is evaporated from the soil surface, the lower soil ψ_m created provides a driving force causing water to move from areas of higher soil ψ_m deeper in the soil to the drier areas near the surface. Because water transport in soils is extremely slow when soil ψ_m is very low, the effect of evaporation from the surface is limited to about the first 0.5 m in most soils in Owens Valley over an annual time scale.

In a similar manner, water from saturated soil below a water table flows upward by capillarity in the soil column in response to gradients in soil ψ_m. Water rises from a water table until the hydraulic head is equal to the soil ψ_m. This rise usually is about 1 m in most soils in Owens Valley but can vary considerably with soil texture (M.R. Welch, U.S. Geological Survey, written commun., 1988).

For the remainder of this report, soil ψ_m will be referred to in pF units. Schofield (1935) defined pF as the base 10 log of soil ψ_m in centimeters of water. This logarithmic scale is used because the relation between θ and soil ψ_m is log linear, at least in soils that have ψ_m greater than field capacity (about 2.3 pF). pF units are always positive and can be converted to the equivalent soil ψ_m in kilopascals using equation 1.

$$\text{Soil } \psi_m \text{ in kilopascals} = -0.098 \text{ (antilog soil } \psi_m \text{ in pF units).} \qquad (1)$$

To avoid confusion, one should remember that the higher the soil ψ_m in pF, the lower (more negative) the soil ψ_m in kilopascals.

A conceptual model of how soils in the shallow ground-water areas of Owens Valley respond to normal conditions is needed to understand changes in soil water conditions at the drawdown sites. Figure 7*A* shows an idealized soil ψ_m profile from a hypothetical site that has a water-table depth of 3.5 m without plants near the end of summer. The upper 0.5 m of the profile has the highest soil ψ_m as the result of evaporation from the surface. The middle part of the curve shows the soil ψ_m at about field capacity. Water in this part of the curve is mostly from rain that infiltrated the soil from above. Water in excess of that needed to maintain field capacity infiltrated through the soil column by gravitational forces. The part of the curve within about 1 m of the water table

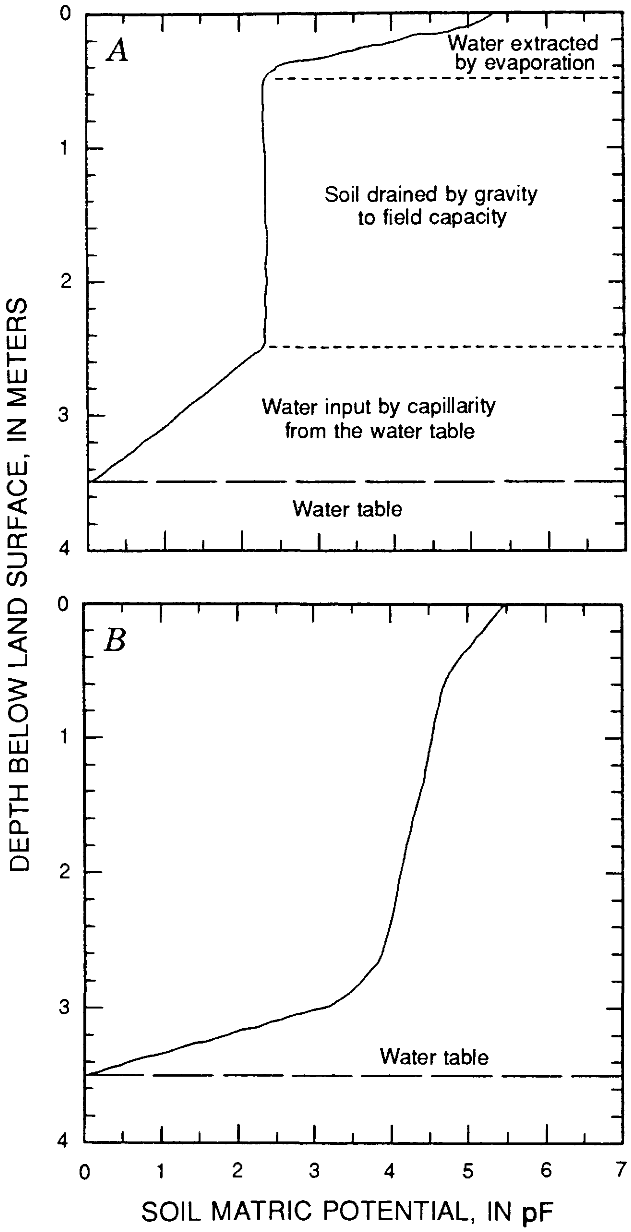


Figure 7. Idealized soil matric potential profile in soil with water-table depth of 3.5 meters near end of summer. *A*, Without plants. *B*, With plants.

has θ in excess of field capacity because water is moving upward from the water table by capillary forces.

Figure 7*B* shows another idealized profile of the same soil but with plants near the end of the summer. Plants have extracted enough water from the soil to increase soil ψ_m to about 4.5 pF at about 1 m below land surface. Studies in Owens Valley (Groeneveld, 1986) show that root densities are greatest at a depth of about 0.4 m and show an exponential decrease with depth below that. Therefore, in a plant community, the greatest capacity for extracting water from the soil is approximately in the upper 1.0 m where root masses are greatest. It is important to note that roots at all depths have about the same capacity to extract water from the soil. Therefore, the end segment of root, regardless of the depth, is absorbing water at about the same rate. Measured bulk soil water or soil ψ_m show changes that reflect root densities, not the efficiency of individual roots. Data collected for this study indicate that when the plants first come out of winter dormancy in March or April, water is used from the soil profile from the top down, corresponding to root densities. The maximum soil ψ_m normally attainable due to withdrawal of water by roots of the plants studied is about 4.3 pF. Once the soil ψ_m reaches that level, little further extraction of water is possible; therefore, the plants must use more available water deeper in the profile where root densities are lower. This extraction of water results in an overall decrease of water availability to the plants as the shallow soils dry. Although available water is most abundant near the water table, root densities are so low that only a small proportion of the plants' water demand is obtained from this area of the soil.

These idealized profiles apply to all soil types found in the study area. Soil texture may affect the depth to which evaporation can effectively remove water or the height of capillarity, but the soil ψ_m values are applicable to any soil. Soil water characteristics indicate that the quantity of water in one soil at a ψ_m of 2.3 pF may be very different than in another soil at the same ψ_m. This primarily is the result of differences in soil texture. Fine-textured soils have much greater water-holding capacity than coarse-textured soils. In general, the water available to a plant is the difference between θ at a ψ_m of 2.3 pF and θ at a ψ_m of about 4.3 to 4.6 pF, depending on the water-extraction capability of the particular plant. Therefore, much more water is available to a plant between these two ψ_m values in finer textured silty clay soils than in sandy soils. This has important implications for plant survivability when water tables are drawn down because fine-textured soils retain a great deal more water after drainage than do coarse-textured soils. Therefore, fine-textured soils should be able to support existing vegetation for a longer period of time in the absence of water movement from the water table.

When the water table declines, water drains out of the soil until the ψ_m reaches about 2.3 pF. Depending on the texture of the soil and the density of the vegetation, the water remaining in the soil will sustain the plants for a certain amount of time after capillary contact with the water table is broken. Assuming that enough water is left behind by the water-table decline, the plants should be capable of growing additional roots deeper in the soil profile to use this water if needed. If there is enough water in the newly drained soil, the plants will be able to sustain near-normal densities as they grow roots to obtain the deeper water. If there is not enough water to allow the plants to function normally as they grow new roots, vegetation density will decrease, and some of the less drought-tolerant plants will die.

According to the conceptual model of θ and soil ψ_m for the soils in Owens Valley, the following is an outline of how the soil water in a typical soil profile changes under normal conditions. During the winter dormant period when most rainfall occurs, soil profiles are recharged with rainwater from surface runoff or from capillary movement from the water table. If water content from rain or runoff exceeds normal field capacity, the remaining water infiltrates to the water table. If rainfall is insufficient to replace the water extracted by vegetation during the previous summer, the soil absorbs water from the top down. That is, the upper part of the soil adsorbs water until soil ψ_m reaches about 2.3 pF before water infiltrates to deeper soil. When the plants come out of dormancy in March, they use water rapidly to support new growth. Water is drawn from the shallowest zones first, where root densities and nutrients are greatest. These zones normally are near field capacity after winter rains. If this shallow zone has not been recharged to field capacity, the plants withdraw more water from the deeper soils, which have much lower root densities. With a normal water table in place at a depth of 2 to 3 m, the deeper roots are capable of drawing enough water from the capillary zone to sustain the plants even when rainfall does not fully recharge the upper soil zone. This capillary water above the water table can be compared to a water bank in that the water is always available to the plants but is normally not needed until the shallow soil water becomes less available.

Most of the discussion of soil water conditions at individual study sites refers to ψ_m because in the absence of large amounts of dissolved salts, ψ_m is the primary measurement of the quantity of suction that needs to be overcome by plant roots to extract the available water from the soil. In some soils, particularly in the shallowest 0.5 m, considerable buildup of salts occurs. As a result, the osmotic potential (ψ_π) of total soil water potential is high (Sorenson and others, 1989). The primary extraction of water by roots then occurs at depths greater than 0.5 m, where ψ_π is usually so much less than ψ_m that it can be ignored.

Because soils in Owens Valley are so heterogeneous, there are several changes in soil texture in most soil profiles. Each soil texture has a different characteristic curve relating θ to ψ_m, and thus one cannot tell by looking at θ data what the associated ψ_m value is unless the characteristic curve is known. By looking at a profile of ψ_m values derived using the filter-paper method (Sorenson and others, 1989), one can see where in a soil profile water is being input or extracted. To illustrate this, the profiles of θ and soil ψ_m from transect D1 are shown in figure 8. These and all other illustrated profiles of individual points of soil ψ_m show a mean value of ψ_m at depth and the 0.1-m increment above and below. This was done to compensate for slight differences in soil volume obtained from each auger sample. The October 1986 profiles shown in figure 8 indicate that from 1.05 to 6 m, θ ranges from 5 to 32 percent, and ψ_m ranges from 1.7 to 2.3 pF. The differences in θ are caused by the difference in water-holding capacity of the silty soil from about 1 to 3.2 m from that of the coarser sandy soil below 3.2 m. Less water is in the deeper sandy soil, but the force the plants must overcome to extract it from the soil is no greater than in the silty, intermediate-depth soils.

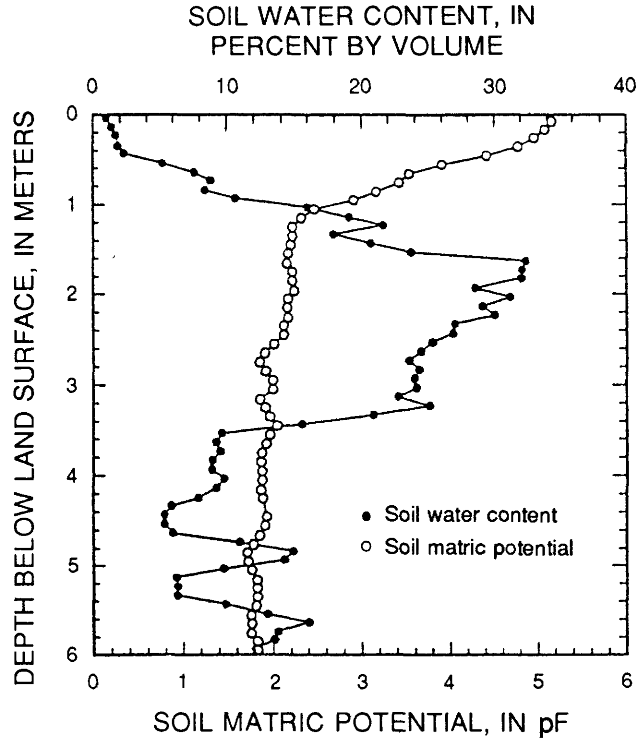


Figure 8. Soil water content and soil matric potential in soil profile at transect D1, October 1986.

Site K

At site K, the fast-drawdown site near Independence, pumping began in March 1984 and continued through October 1986. Maximum water-table drawdown at monitoring well M varied seasonally and ranged from 3.7 to 4.3 m (fig. 6*A*). Drawdown ranged from 2 to 3 m at well E adjacent to transect K3 (fig. 6*B*). Because of the fine texture of the silty clay soil, infiltration of water from the surface was slow and usually not detectable below the first 0.5 m, except after periods of heavy rain such as occurred in the winter of 1985–86. Profiles of soil ψ_m from the five transects at this site (fig. 9) show that recharge to field capacity did not occur in the upper 1 to 2 m of soil during the winter. Seasonal variation in soil ψ_m usually was confined to the upper 0.6 m, where evaporation increases soil ψ_m (during summer), and either precipitation wets the area or soil water equilibrates with the wetter soil deeper in the profile (during winter). Changes in ψ_m in soils deeper than 0.6 m primarily are caused by removal of water by plant roots and input of water by capillary flow from areas of greater θ near the water table.

At transect K1, the first profile taken in September 1983 indicates a maximum soil ψ_m of 4.3 pF (at a depth of about 1 m) for the soil deeper than 0.5 m (fig. 9*A*). This maximum soil ψ_m occurred in nearly all profiles at all five transects and seems to be the maximum soil ψ_m to which the plants can efficiently absorb water. Maximum soil ψ_m in any soil profile was always in the upper 1 m of soil, because this is where the rooting density was greatest. In deeper soil, the roots probably are capable of extracting water to the same soil ψ_m as in the shallow soils, but because the root densities are much less, the soil ψ_m of a particular bulk soil sample would indicate a lower soil ψ_m than actually is in the immediate area of a particular root.

Figure 9*A* shows soil ψ_m profiles for September or October 1983, 1984, and 1986 at transect K1. Because these profiles were taken at the end of the growing season, they presumably represent the driest soil conditions during the year. There is little difference between the profile collected in September 1983 and the one collected about 1 year later. In fact, for the depth interval 1.0 to 1.9 m, soil ψ_m was less in the 1984 profile after the drawdown had occurred. The profile for October 1986 shows increased soil ψ_m at 0.5 to 1.0 m and deeper than 1.5 m. None of the profiles taken after the drawdown shows a soil ψ_m greater than 4.3 pF, except in the upper 0.5 m. The increased ψ_m in the soil deeper than 1.5 m in the October 1986 profile indicates that the plants grew their roots deeper and withdrew water from zones that had been drained following drawdown. The presence of apparently live plant roots in soil samples taken from that part of the soil profile below the

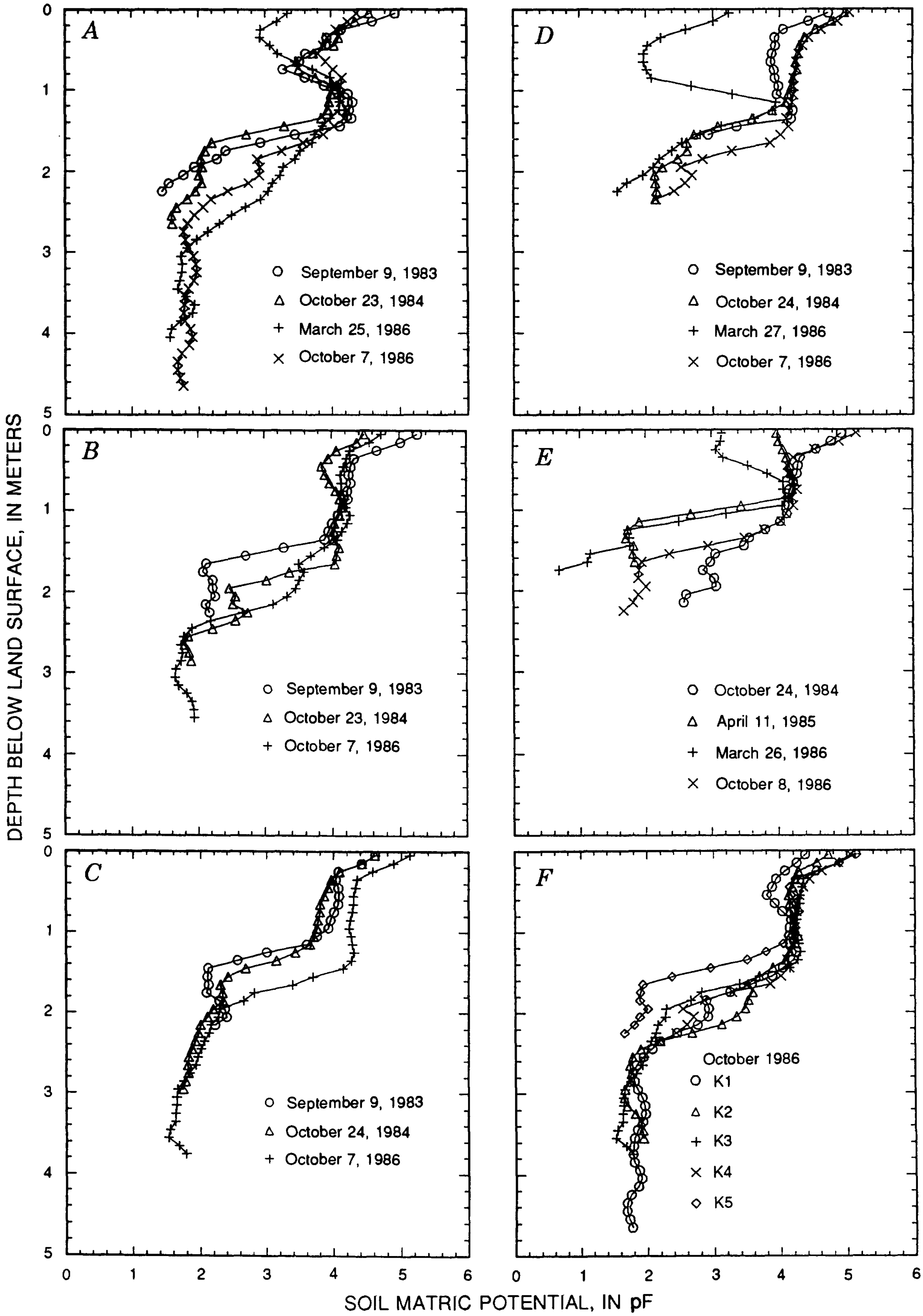


Figure 9. Soil matric potential profiles at transects K1–K5. *A*, Transect K1. *B*, Transect K2. *C*, Transect K3. *D*, Transect K4. *E*, Transect K5. *F*, Transects K1–K5.

prepumping water table, where no roots existed prior to pumping, confirms this assumption. The soil ψ_m profile taken at transect K1 in March 1986 (fig. 9*A*) had a higher soil ψ_m from 1.7 to 2.9 m than did the profile taken in October 1986. This higher soil ψ_m would not be expected unless there was a rise in the water table during the summer of 1986. This water-table rise did not occur as indicated by minimal changes in water levels measured in monitoring wells; however, there was a substantial leakage of water from the discharge lines of one of the pump-equipped wells in March 1986 that caused temporary ponding of water at transect K1. Enough of this water may have infiltrated into the soil that the plants drew more water from the upper 1 m of soil and did not need to draw water at the 2- to 3-m depth.

The soil ψ_m profiles taken at transect K2 show nearly the same pattern as at transect K1, reaching the maximum soil ψ_m of 4.3 pF at about 1 m (fig. 9*B*). The range of soil ψ_m values was smaller at 1 to 2.5 m at transect K2 for the period of monitoring than at transect K1.

Soil profiles taken at transect K3 showed patterns similar to those at transects K1 and K2, except that soil ψ_m approaches field capacity at depths that were about 0.2 to 0.5 m shallower (fig. 9*C*). This difference would be expected because the water table at this transect was shallower than at the transects closer to the pumped wells. At transect K3, the entire October 1986 profile above 2 m had higher soil ψ_m values than in the samples collected the previous autumn, indicating a drying trend in the soil during the period of drawdown.

Soil matric potential profiles at transect K4 also showed a drying trend from September 1983 to October 1986 (fig. 9*D*). Virtually no change in soil ψ_m was noted between October 1984 and October 1986 in the upper 1 m. The increased soil ψ_m between 1.4 and 2.2 m between 1984 and 1986 may have been caused by root growth into this zone, as was believed to be the case at other transects. The soil profile for March 1986 showed a large decrease in soil ψ_m in the first 1 m in comparison with previous and subsequent profiles. This profile was collected after the wet winter of 1985–86 and showed that water infiltrated from the surface to a much greater extent than at the other transects at site K. This infiltration would be expected because the soil in the upper 1 m at this transect was a coarser sand than at the other transects. In addition, because of the smaller water-holding capacity of this soil, infiltration of a given quantity of water would decrease the soil ψ_m more than at sites with fine-textured soils.

Soil profiles at transect K5 were similar to the other transects at site K in the upper 1 m (fig. 9*E*); however, because this transect had no drawdown resulting from the pump-equipped wells, the soils were much wetter below 1 m. In common with the other transects, the maximum soil ψ_m of 4.2 to 4.3 pF occurred at a depth of about 1 m. Because this transect was selected as a control, the soil profiles at this transect are assumed to show what the other profiles would have looked like if there had been no drawdown. What the soil profiles do show is that, prior to drawdown, the bulk of the water absorption by roots was from the top 1.5 m of soil. Below 1.5 m, soil ψ_m fluctuated seasonally as the plants absorbed water during the growing season and the water was then replaced by capillary flow or rainwater infiltration during the dormant season.

Figure 9*F* shows profiles of soil ψ_m at transects K1 through K5 in October 1986, shortly before the pumping was stopped. The profiles are similar, except for some variation around 2 m; the profile for transect K5 shows the effects of the shallower water table at this control site. The profiles show the same effects on soil ψ_m at each of the drawdown transects, regardless of the amount of drawdown. For the short period of this study and with the high precipitation in the winter of 1985–86, available water in the first 1 m or less of the newly drained soils was enough to supply the plants so that there was no need for the water left by further decline in the water table.

Site D

Pumping at site D, the fast-drawdown site near Bishop, began in October 1984, and the initial water-table drawdown near the pump-equipped wells was about 5.5 m. The first profile of soil ψ_m taken at transect D1, 23 m from the pump-equipped wells, after the initial drawdown in March 1985 shows that the soil down to 5 m had a nearly uniform soil ψ_m of 1.7 to 2.2 pF (fig. 10*A*). This indicates that the soil was still draining and had not reached field capacity. Subsequent soil profiles for March and October 1986 show that the soil below 1 m remained at a ψ_m of near 2 pF. The highest soil ψ_m, indicating the driest profile, was obtained in September 1983 before the water-table drawdown. In this profile, soil ψ_m below 1.4 m increased to greater than 2 pF. These profiles indicate that drawdown at this site had little effect on ψ_m in the soil. During the first season of drawdown, equipment failure early in 1985 twice resulted in a nearly complete recovery of water levels in the monitoring wells at this site (fig. 6*C*). As a result, the soil profile or the plants were not expected to be affected in 1985. The water-table drawdown was maintained throughout the 1986 growing season, but this was not enough time to cause water stress in the plants, because the upper part of the soil was fully recharged by rainfall from the comparatively wet winter of 1985–86.

The soil profiles at transect D2 were nearly identical to those at site D1 (fig. 10*B*) with the exception of

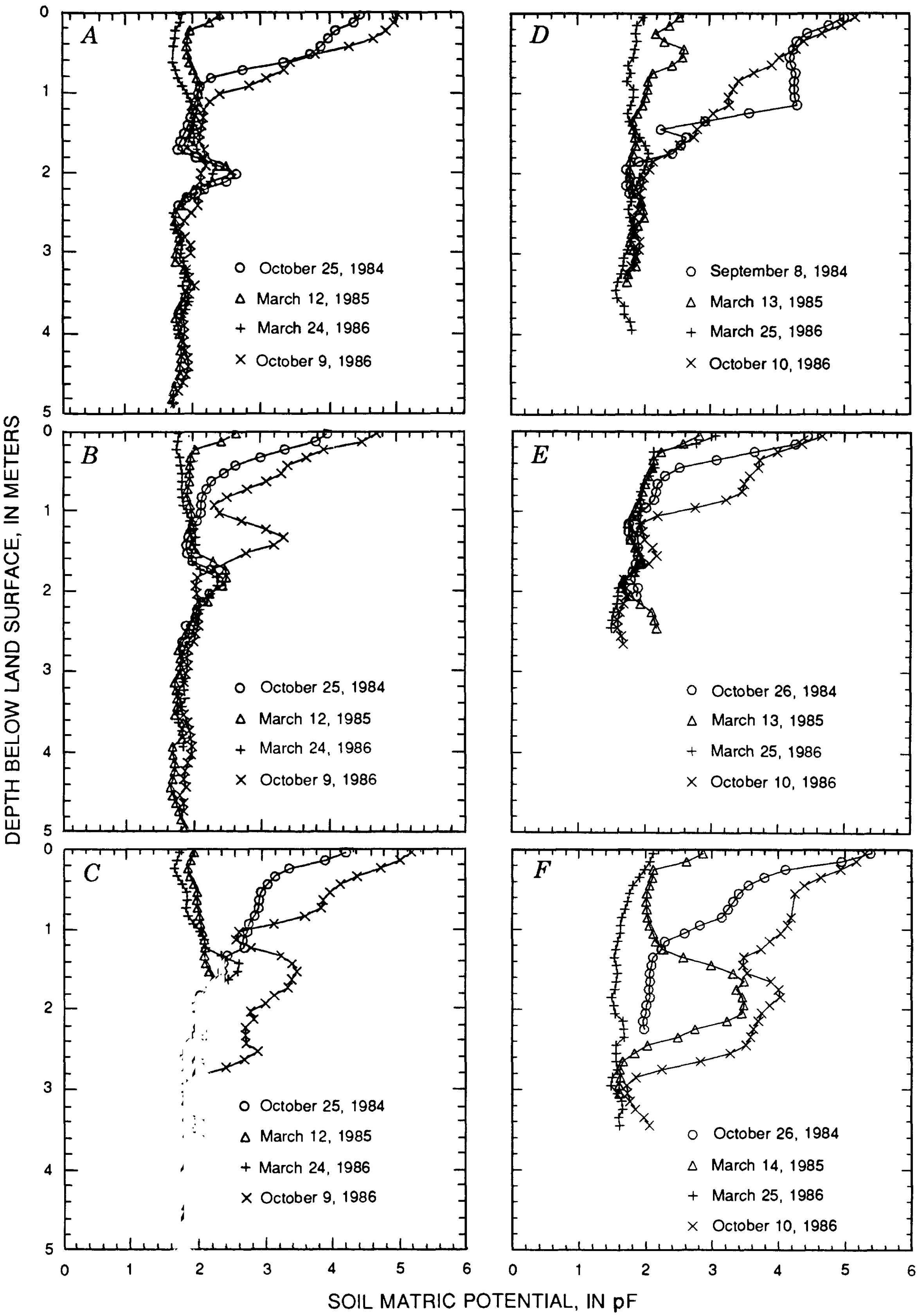


Figure 10. Soil matric potential profiles at transects D1–D6. *A*, Transect D1. *B*, Transect D2. *C*, Transect D3. *D*, Transect D4. *E*, Transect D5. *F*, Transect D6.

the October 1986 profile. Very little water was drawn from deeper than about 1.3 m until the summer of 1986.

Water-table drawdown at transect D3 was about 3 m. Data for this transect, unlike transects D1 and D2, indicated that water was being extracted between 1 and 3 m as shown by the soil ψ_m profiles for March and October 1986 (fig. 10*C*). Measurements of θ in these profiles indicate that a total of 517 mm of water was in the upper 2.5 m of soil in March 1986 at transect D1, and 339 mm at transect D3. Not only was the total water available at transect D3 less than at transect D1, but the total water used in the upper 2.5 m between March and October 1986 was 108 mm at transect D3 as opposed to 79 mm at D1. The reason for this increased water use at transect D3 probably was the greater vegetative cover at this site in comparison with transects D1 and D2.

At transect D4, water was used to a depth of about 2 m during each growing season (fig. 10*D*). This depth was the same for October 1986 as it was for September 1984 before the water-table drawdown, which indicates that soil water conditions at this transect did not change appreciably during artificial drawdown.

At transect D5, the profile for October 1986 is drier for most of the first meter than is the profile for October 1984 (fig. 10*E*). However, soil ψ_m is near field capacity at nearly the same depths in both profiles, indicating little change in soil water conditions as a result of artificial drawdown.

The soil ψ_m profiles from transect D6 (fig. 10*F*) vary with depth and time more than the profiles from the other transects at this site. The profile of soil ψ_m for October 1984 indicates a much lower soil ψ_m than the one for October 1986 as a result of precipitation that occurred in September 1984. The March 1985 profile differs from most March profiles at other transects in that there is a zone around 2 m that was not at field capacity. This part of the profile was, in fact, drier than it had been the previous October. Transpiration during the winter, although much reduced from summer use, is the likely explanation for the drier zone in this March 1985 profile. The large variations in soil ψ_m at this transect are due partly to the coarse sandy soil. In this soil, changes of only 4 to 7 percent in θ result in changes in soil ψ_m of 1.9 to 3.5 pF. Because there was very little drawdown at this site resulting from experimental pumping, changes in observed soil water conditions were not affected by water-table changes.

Site H

At site H, the slow-drawdown site near Independence, pumping began in June 1984 and continued until September 1987. Initial drawdown from the 0.9 m prepumping water level was about 1.8 m. This drawdown was maintained until October 1985, when pumping was increased in an effort to get an additional 1.8 m of drawdown. This second increment of drawdown was only about 1.2 m until about April 1986, when water levels slowly declined an additional 0.5 m.

Soils in the top 2 m at this site are silty clays and are similar to those at site K. From a depth of about 2 to 3 m, the soil is fine to coarse sand, much like the soils typical of sites B and D in the Bishop Basin. This change in soil texture can be recognized by comparing readings of θ and soil ψ_m (fig. 11). The soil at 0.3 to 0.5 m has a soil ψ_m near 4 pF and a volumetric water content (θ_v) of 28 to 30 percent. By contrast, the sandy soil at 2.8 m has a soil ψ_m close to field capacity and a θ_v of 5 to 6 percent.

Profiles of soil ψ_m for this site show that very little water infiltrated from the surface due to the fine soil texture. Figure 12 shows soil ψ_m profiles taken in March from 1984 through 1987. None of these profiles show a decreased soil ψ_m in the upper 0.2 m that is characteristic of soils at sites B and D just after the wet season. During pumping, the soil gradually dried as indicated by increased soil ψ_m in each succeeding profile. The maximum soil ψ_m of 4.3 pF that occurred at all site K transects was not reached until March 1987. Between March 1986 and March 1987, after the second increment of drawdown had occurred, soil ψ_m increased greatly at a depth of 1.8 to 2.8 m. This increase probably was caused

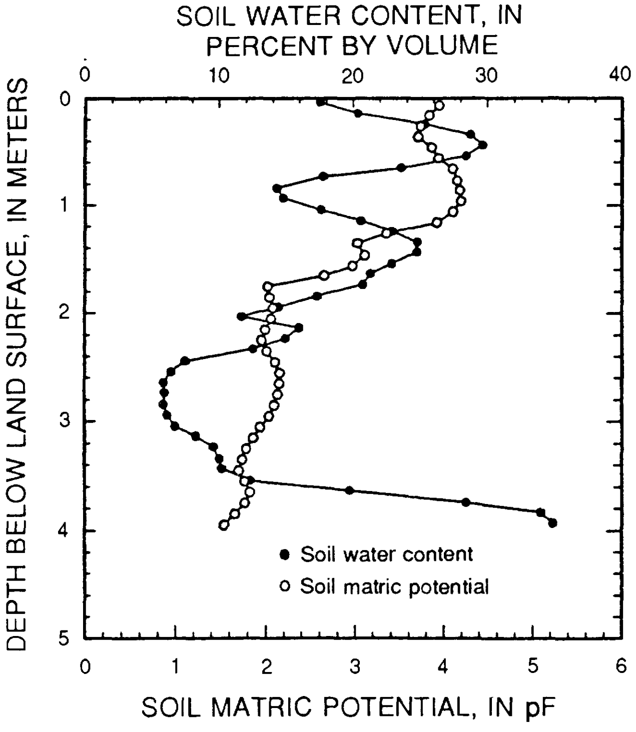


Figure 11. Soil water content and soil matric potential at transect H1, March 1986.

by additional root growth into this zone and resulting water use during the spring and summer growth period. During this time period, additional water also was withdrawn from the top 1.5 m of the soil profile, as indicated by the increased soil ψ_m.

Site B

Pumping at site B, the slow-drawdown site near Bishop, began in the autumn of 1984, but sustained drawdown was not obtained until January 1985 owing to numerous equipment problems. Water-table drawdown was 1.2 to 1.4 m during the 1985 growing season and a total of about 2 m during 1986 (fig. 6*F*).

Profiles of soil ψ_m (fig. 13) show that there was little change in soil ψ_m below 1 m during the summer of 1984, before drawdown. Water was being supplied by capillarity to the soil from the water table, which was at a depth of about 1.8 m. The profile in March 1985, 2 months after the 1.4-m drawdown, shows that, except for the top 0.2 m, the entire profile was wet to near field capacity. By October 1985, soil ψ_m had increased along the entire profile, reaching a maximum (below 0.5 m) of 4.1 pF. The soil ψ_m profile for October 1985 (fig. 13) was calculated from neutron-probe measurements using the techniques outlined by Sorenson and others (1989).

During the summer of 1985, live vegetation along transect B1 substantially decreased. Precipitation during the comparatively wet winter of 1985–86 wet the soil profile to field capacity to a depth of slightly more than 1 m. Below 1.7 m, soil ψ_m increased, indicating additional water use from this depth during the winter months. The profile for October 1986 indicates a soil ψ_m greater than 4.3 pF at a depth of 1.4 m, which is the deepest point that this high a ψ_m occurred in any of the study transects.

In March 1985, 251 mm of water was in the upper 2.5 m of the soil at transect B1. By October 1985, 158 mm of this water had been used. In March 1986, 248 mm of water was in the upper 2.5 m of this soil, nearly the same as in March 1985. The drier soil below 1 m was offset by additional water from precipitation in the upper 1 m. By October 1986, 171 mm of this water had been used. The total use of water in the upper 2.5 m of soil was greater in the summer of 1986 than in the summer of 1985, even though less live vegetation grew along the transect in 1986.

VEGETATION RESPONSES

Vegetative Cover

Measurements made during this study indicate that vegetation on the floor of Owens Valley is affected by changes in depth to ground water and by the quantity of precipitation falling on the valley floor. The extent and nature of these effects are highly variable and determined largely by local edaphic conditions. Changes in vegetation at each site were assessed by measuring cover repetition using the point-frame apparatus.

Cover repetition was used rather than percentage cover in these analyses because it is more closely related

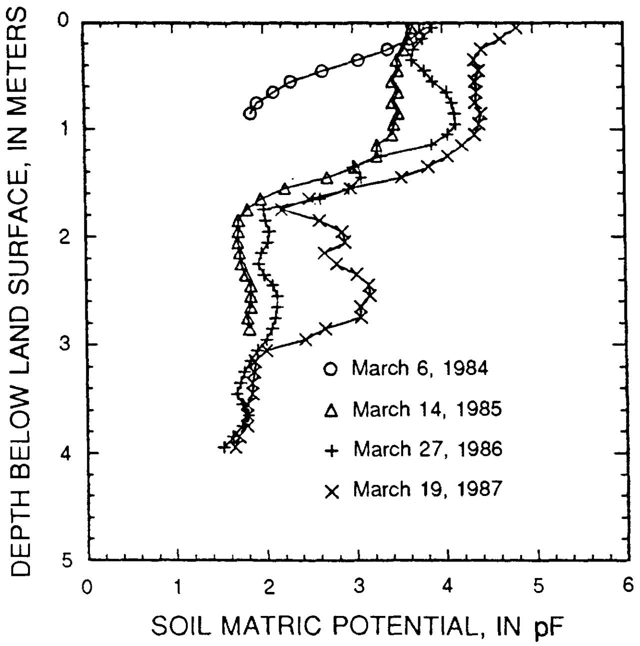


Figure 12. Soil matric potential profiles at transect H1.

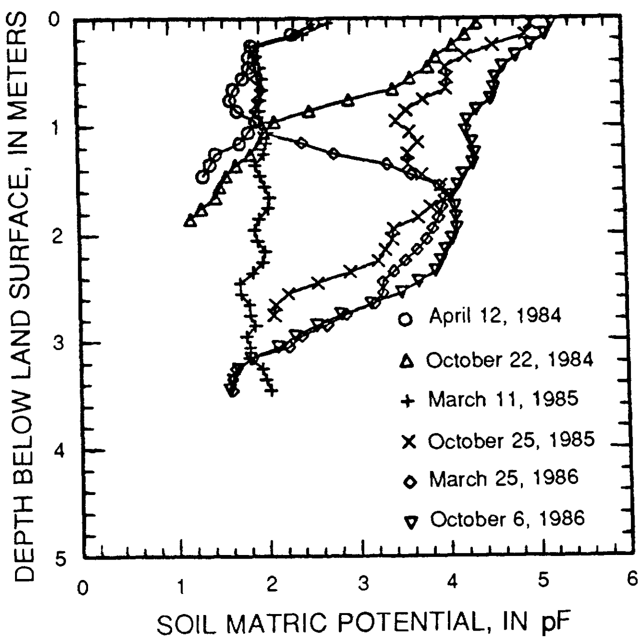


Figure 13. Soil matric potential profiles at transect B1.

Table 1. Percentage cover of plant species, bare soil, and mulch measured at each transect, September 1984

Cover	Transect														
	K1	K2	K3	K4	K5	D1	D2	D3	D4	D5	D6	H1	H2	B1	B2
Artemisia tridentata	0	0	0	0	0	0.4	0.8	3.2	0	0	0	0	0	0	0
Atriplex confertifolia	0	0	0	0	0	1.2	0	.8	0	0	1.6	0	0	0	0
Atriplex torreyi	31.6	19.2	10.4	17.2	22.0	0	0	0	0	0	0	23.6	36.4	3.6	6.4
Chrysothamnus nauseosus	0	3.6	5.2	4.4	6.4	2.8	0	.4	4.0	6.4	6.0	.8	0	5.6	17.6
Distichlis spicata	.4	0	0	0	.4	2.4	10.4	.8	6.8	6.0	5.6	3.6	27.2	18.0	12.8
Glycyrrhiza lepidota	9.2	0	2.0	4.4	8.4	0	0	0	0	0	0	.4	1.2	0	0
Sarcobatus vermiculatus	0	1.6	.8	.4	1.2	6.0	3.2	0	.8	1.6	1.6	0	0	7.6	12.4
Sporobolus airoides	0	0	0	0	0	0	0	0	11.6	8.8	3.6	0	0	6.4	6.0
Other plant species	0	2.4	1.6	0	1.6	.4	.4	0	0	0	.4	.4	.4	0	1.6
Bare soil	20.0	39.6	41.6	22.8	26.0	62.4	54.8	62.8	50.0	47.2	58.8	55.6	6.0	22.8	8.0
Mulch	38.8	33.6	38.4	50.8	34.0	24.4	30.4	32.0	26.8	30.0	22.4	15.6	28.8	36.0	35.2

to leaf area and biomass and is a more sensitive measurement of changes in the plant canopy. Although the plant community at each site is qualitatively uniform as to species composition and character over the period of this study, quantitative differences between transects preclude direct comparison of the percentage cover or cover repetition measurements from one transect to another. This difference can be seen from the variability in percentage cover at each transect for each plant species, mulch (dead plant material), and bare soil in table 1. To allow comparisons between transects, measurements of cover repetition at each transect were normalized to initial, prepumping conditions (September 1983 measurement). Normalized cover repetition was calculated using the following equation:

$$\text{Normalized cover repetition} = \frac{\text{Current cover repetition}}{\text{Initial cover repetition}} - 1. \qquad (2)$$

As a result of this normalization, the initial values for cover repetition at all transects are equal. Differences between normalized measurements at any single transect are a measure of change in cover repetition relative or proportional to initial conditions rather than a difference in actual cover repetition. At each transect, normalized cover repetition is zero for the first measurement. Subsequent measurements are positive for increases and negative for decreases in cover. Multiplying normalized cover repetition by 100 gives the percentage difference between a measurement and initial conditions at the transect.

Response to Precipitation

In the first 2 years of this study, a widespread decline in plant cover occurred at the study sites (fig. 14). Measurements made in 1986 show a slight recovery but were still below initial levels. During the 1984 and 1985 growing seasons, a substantial decrease in cover was measured at all transects regardless of differences in water-table drawdown (fig. 15). Plant-productivity measurements made in 1983 and 1984 at Haiwee Reservoir at the southern end of the valley by Los Angeles Department of Water and Power also show a decline in 1984 (Los Angeles Department of Water and Power, written commun., 1986). The widespread decrease in plant cover is evidence that a valleywide factor affected plant cover.

Changes in plant cover closely corresponded to changes in total yearly precipitation as measured from

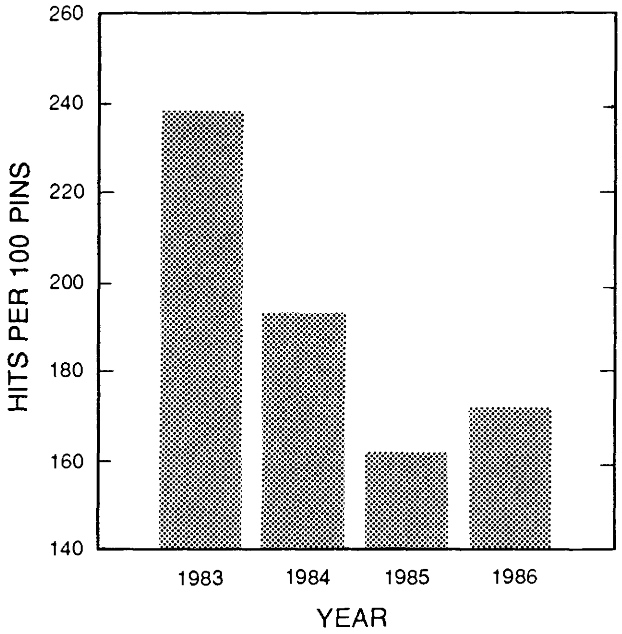


Figure 14. Combined measurements of cover repetition for all sites and species measured in September, 1983–86.

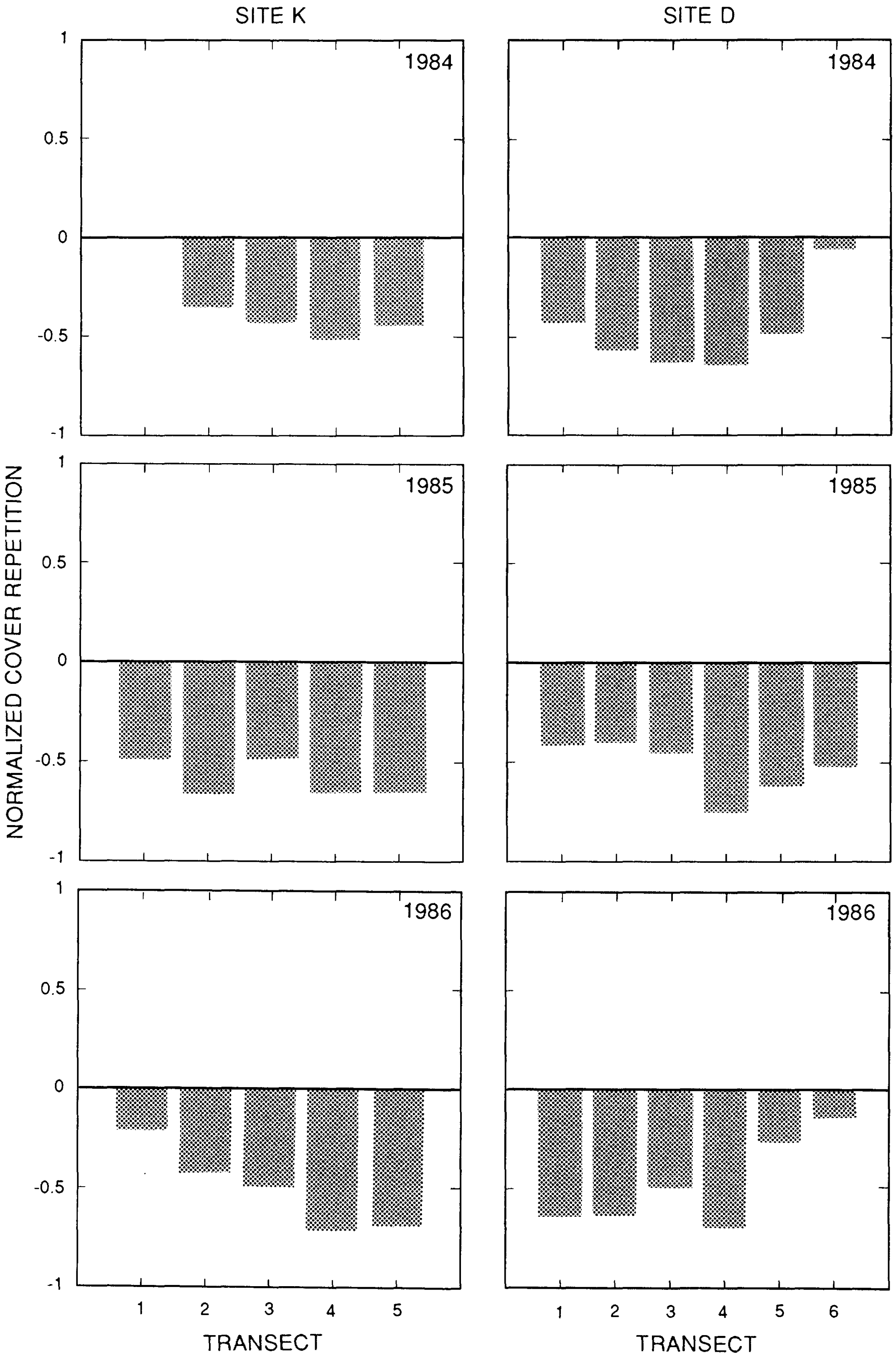


Figure 15. Normalized cover repetition for phreatophytic shrubs at each transect. Each measurement represents combined values of Nevada saltbush (*Atriplex torreyi*), rabbitbrush (*Chrysothamnus nauseosus*), and greasewood (*Sarcobatus vermiculatus*).

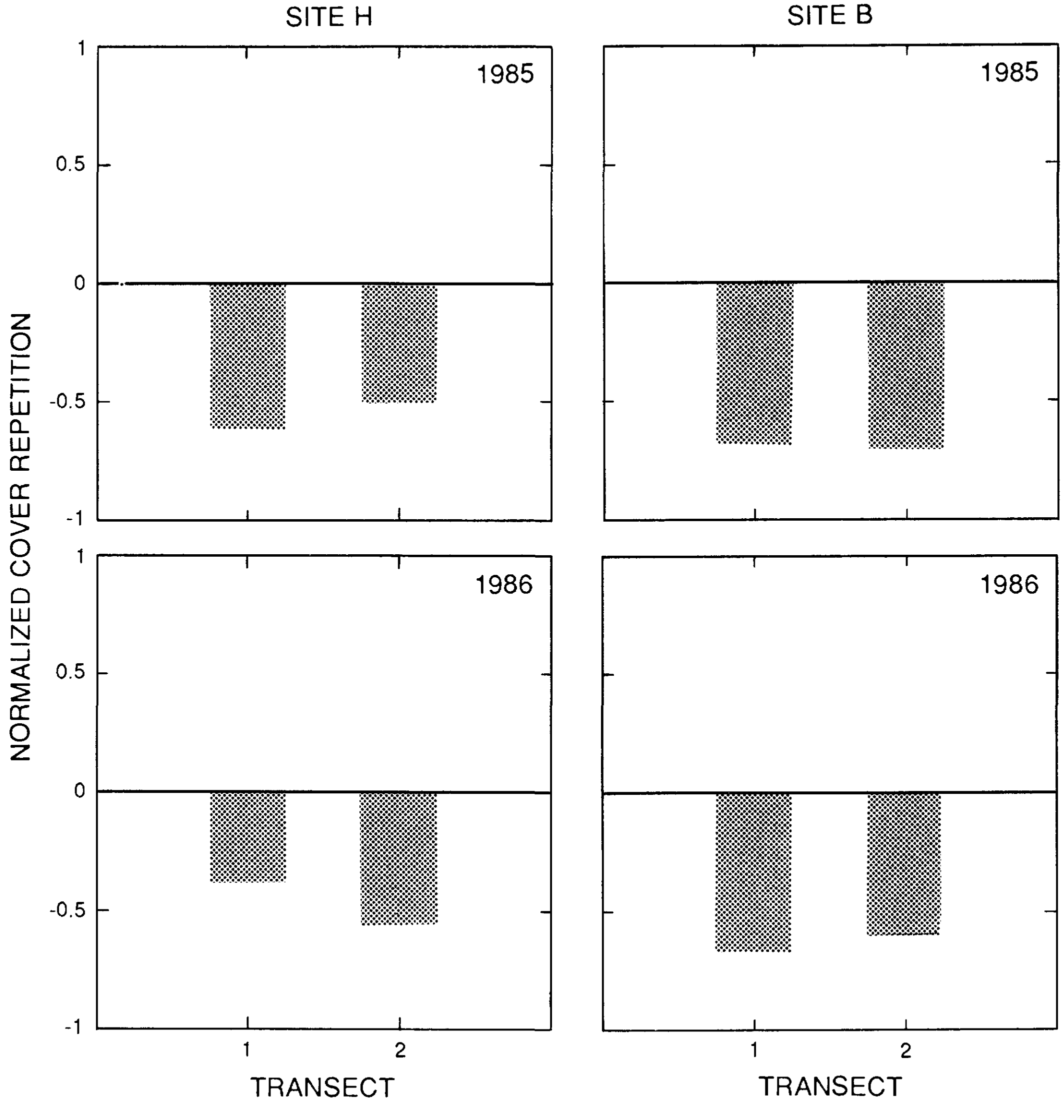


Figure 15. Continued.

November through October (fig. 16). This measurement period represents the annual precipitation for the plants' water-use cycle better than the calendar year. Most of the precipitation falling after October infiltrates and is stored in the soil, where it is available to the plants the following spring when growth begins and water use increases.

In 1983, the year before drawdown, precipitation was about twice the average (greater than 230 mm) in the Bishop and Independence areas. During the following two years, 1984 and 1985, precipitation decreased to about average levels (108 and 136 mm, respectively). During these years, cover repetition progressively decreased. Precipitation in 1986 increased to 192 mm at Bishop and 233 mm at Independence. Cover repetition also increased somewhat in 1986, but it was not as great as in 1983.

The correlation coefficients between cover repetition and precipitation for plants at the fast-drawdown sites are shown in table 2. Plants at each transect were divided into two groups—phreatophytic shrubs and grass species. The phreatophytic shrubs are Nevada saltbush, rabbitbrush, and greasewood; the grasses are saltgrass, alkali sacaton, and basin wild rye. Cover-repetition measurements at all transects in the site were combined before correlation with precipitation in order to characterize the whole site.

Correlation is good at site D [r(shrubs)=0.88] and moderate at site K [r(shrubs)=0.50]. The difference in correlation between these two sites may be due to differences in soil type and topography combined with precipitation patterns. At site D, soil is coarse textured and highly permeable, and infiltration is rapid. Soil at site K is fine textured, and infiltration is considerably slower.

Much of the bare soil, which covers from 20 to 40 percent of the transects at this site, is characterized by smooth areas or slicks between low vegetated mounds. The smooth surface of the slicks, combined with low infiltration rates, facilitates runoff and decreased infiltration.

In 1983, relatively abundant precipitation was evenly distributed over the winter months. In 1986, much of the precipitation fell during a few intense storms (more than 40 percent of the total annual precipitation fell during a single storm in February). The small but frequent amounts of precipitation occurring in 1983 allowed greater infiltration at site D than in 1986, when more water may have been lost to runoff at site K than at site D because of differences in topography, soil type, and rainfall intensity. This would result in less recharge to the upper soil levels and less soil moisture available to plants.

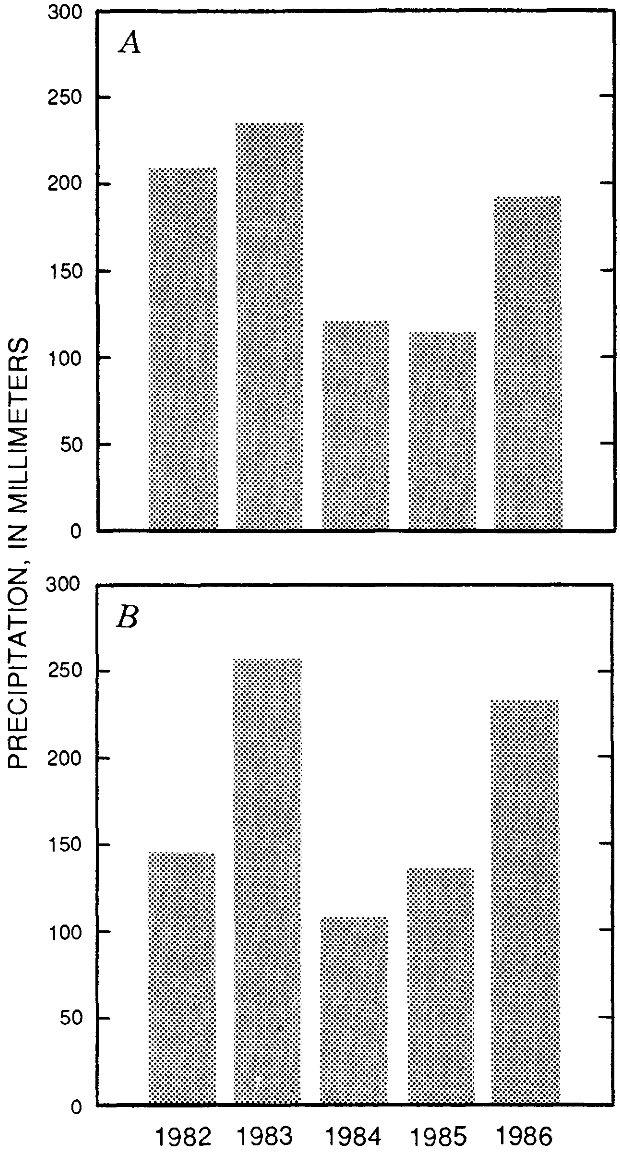


Figure 16. Seasonal precipitation at (*A*) Bishop and (*B*) Independence during each growing season, 1982–86. Values are combined monthly totals from November of the preceding year through October of the year indicated. From National Oceanic and Atmospheric Administration monthly summaries.

Table 2. Correlation coefficients for cover repetition and precipitation for phreatophytic shrubs and grasses for each transect at sites K and D

[--, no data]

Transect	Shrubs	Grasses
K1	0.19	--
K2	.62	--
K3	.55	--
K4	.42	--
K5	.36	--
K combined	.50	0.46
D1	.51	.48
D2	.58	.45
D3	.84	.90
D4	.80	.56
D5	.98	.68
D6	.65	.51
D combined	.88	.69

Plant-cover measurements at slow-drawdown sites H and B (fig. 17) began in 1984. At site H, transects H1 and H2 show a decrease in plant cover from 1984 to 1985. In 1986, cover repetition increased following that season's increased precipitation.

Plant cover also decreased from 1984 to 1985 at transects B1 and B2. Cover repetition in 1986 increased at transect B2, but not at B1. As a group, phreatophytic shrubs at transect B1 showed no change in cover repetition between 1985 and 1986.

Response to Changes in Depth to Ground Water

In order to evaluate the effect of water-table drawdown on plant cover, the measurement of changes in plant cover induced by water-table drawdown must be separated from those changes induced by precipitation. The close proximity of each site's transects should result in equal distribution of precipitation among the transects. If one assumes that the effect of precipitation on plant cover also is uniform at each site, differences in the variation between transects may be the result of changes in the depth to the water table. This assumption is reasonable at all sites except site K, where the presence of the largely impervious slick areas alternating with mounds occupied by plants means that infiltration of precipitation likely varies from one transect to another and along a particular transect.

Correlation coefficients shown in table 3 indicate a significant positive correlation at site K between normalized cover repetition and drawdown for all major species present in 1986. Plant cover at this site decreased least at transects with greatest drawdown. Because a phreatophyte by definition depends on a shallow water table for its water requirements, a greater decrease in plant cover was expected at transects where the water table was lowered. This apparent contradiction may be due to soil and water-table conditions at this site before the water table was lowered. Before pumping began in the spring of 1984, the water table was only about 0.5 m deep at the transects closest to the pump-equipped wells. Historical records indicate that the water table was unusually high at this time. The shallow water table thus limited the rooting zone to a small zone of saline soil between the surface and the water table. The extremely high specific conductances of water in the upper regions of the soil (less than 1.0 m depth) at transects K1 and K2 (table 4) indicate a high concentration of salts resulting from deposition in the soil as water evaporated from the surface. In some areas, salt deposits formed a crust on the soil surface. As the water table was lowered, the roots grew deeper into the soil. The larger volume of soil at field capacity within reach of the roots after drawdown resulted in a greater quantity of less saline water available to the plants.

Transects K4 and K5 lacked the saline zone in the upper 1 m of the soil that existed at transects K1, K2, and to a lesser extent, at K3. Cover at transects K4 and K5 declined more each year than did cover at K1 and K2. The cover at K3 declined in 1984 and remained nearly the same for the next two seasons, a pattern intermediate between the others.

The effect of drawdown at site K seems to be dependent on the existence of a highly-saline soil in the upper part of the soil profile combined with an unusually shallow water table. Rather than limiting the supply of water to these plants, lowering the water table increased the quantity and quality of the water available to them.

Soil conditions at site H were similar to those at transects K1 and K2. The water table was shallow, about 1 m below land surface, before pumping began in June 1984. Specific conductance in the upper 1 m also was similarly high (table 4). The plants responded to drawdown in a similar manner by using water stored in the newly drained soil below the prepumping water table. Normalized cover repetition decreased much less at site H than at the control transect K5 (fig. 15).

At site D, drawdown seemed to cause decreased plant cover for some species. Correlation coefficients (*r*) of greasewood and saltgrass indicate a strong negative relation between cover repetition and drawdown (table 3). That is, when drawdown increased, cover decreased for these species. Rabbitbrush and alkali sacaton show no significant relation to drawdown at this site. The phreatophytic shrubs as a group recovered to a great extent following increased precipitation in 1986 at the two transects with the least drawdown (fig. 15). Drawdown at these transects, D5 and D6, was less than 0.9 m. Those transects with a drawdown of 1.5 m or greater (D1 through D4) had the greatest decreases in cover. Because θ and soil ψ_m were almost identical below 1 m for all transects at this site, the correlation seems to be related to a change in the water table only and not to soil water conditions.

From 1984 to 1985, normalized cover repetition at site B decreased along with precipitation, showing the same pattern as the other sites in this study (fig. 15). However, 1986 measurements showed considerable variation between species. Figure 18 shows changes in normalized cover repetition for the major plant species on transects B1 (drawdown) and B2 (control).

Cover repetition for Nevada saltbush followed the typical pattern of a large decrease during 1985 and a moderate increase in 1986. In both 1985 and 1986, normalized cover repetition was greater at transect B2 than at B1.

Cover repetition for greasewood was only slightly less at transect B2 than at B1 in 1985 and 1986, indicating that the 2 m of drawdown at this site did not adversely affect this species. At site D, where drawdown was greater (as much as 5 m), the decline in the water table seemed to have a significant effect on cover repetition for this species (table 3).

In 1985, normalized cover repetition for rabbitbrush and saltgrass decreased at transects B1 and B2. In 1986, these two species at B2 recovered slightly, but all individuals of the species along transect B1 died. As stated in the previous section, the soil at B1 dried (to a soil ψ_m of 4.3 pF) deeper than at any other transect. Rabbitbrush and saltgrass apparently could not survive soil drying to that extent. Rabbitbrush showed no correlation to the amount of drawdown at site K, where drawdown was greater than at transect B1, but because soil did not dry as much, the plants were not greatly affected.

Xylem Pressure Potential

In a transpiring plant, water moves from the soil into the roots through stems to the leaves, where it evaporates to the atmosphere. This moving stream of water, often referred to as the soil-plant-atmosphere continuum, moves in response to water potential gradients created by an atmospheric demand for water vapor (Slatyer, 1967). The atmospheric demand for water combined with resistance to flow in the system results in negative pressure potentials developing within the water-conducting tissues (xylem) of the plant stems and roots. A major source of resistance is in the soil. As a soil dries, its ability to conduct water decreases, and resistance to flow increases.

Xylem pressure potential is the most useful single measurement of the degree of water stress (Kramer, 1983), because it integrates the effects of soil and atmospheric conditions. The use of the pressure chamber to estimate xylem pressure potential has gained acceptance by plant physiologists because it is simple to use and not subject to as many obvious errors as are other methods, such as psychrometric and liquid equilibrium methods. Xylem pressure potential was measured in this study to monitor the water status of plants during the growing season and during periods of water stress caused by high atmospheric demand and low soil water availability. Xylem pressure potentials are referred to in this text in megapascals (MPa). These measurements are always negative, and a lower (more negative) number indicates stronger suction or greater water stress.

Measurements of xylem pressure potential were made two times each day: predawn, when atmospheric

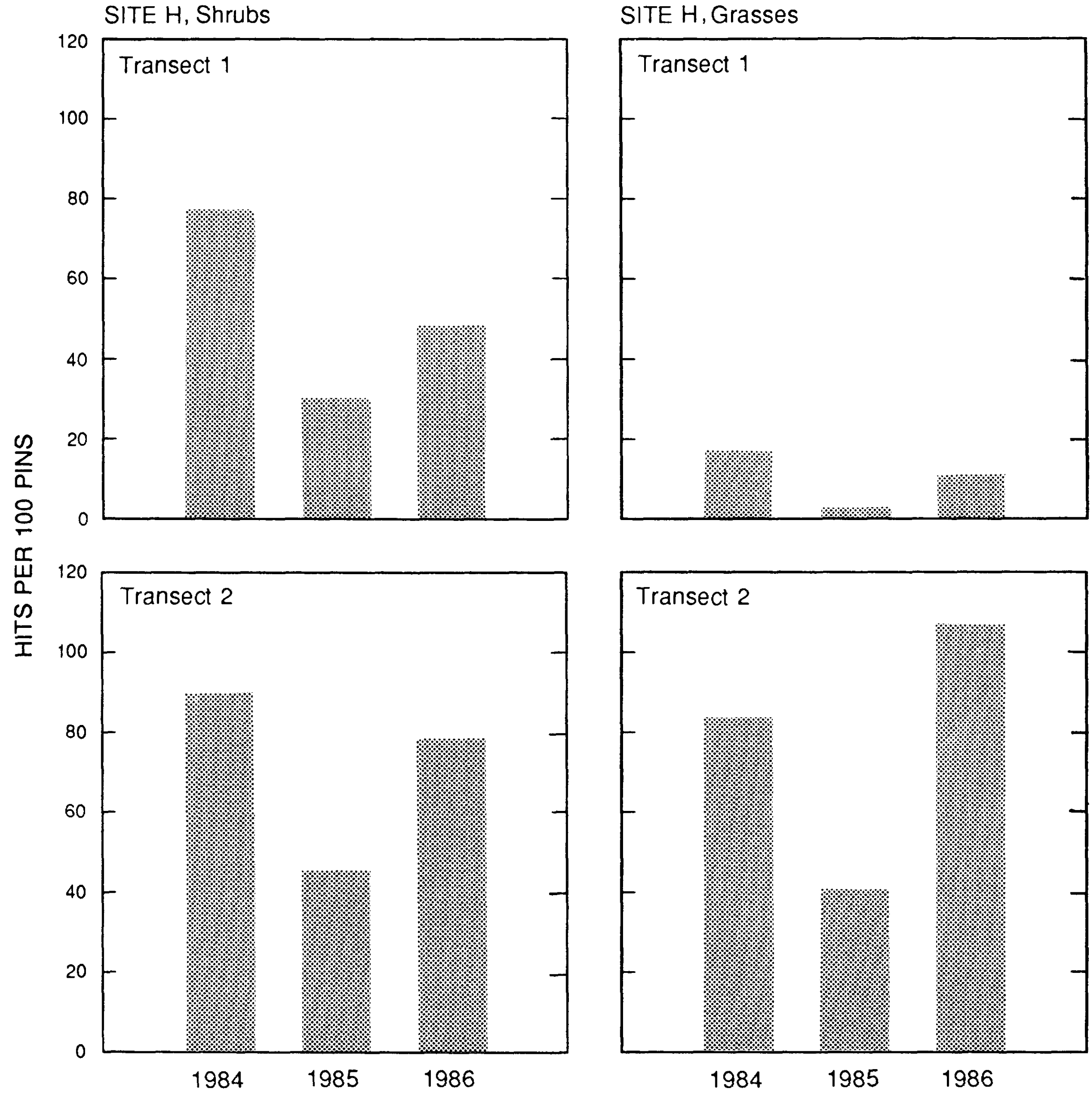


Figure 17. Cover repetition measured in September, 1984–86, for phreatophytic shrubs and grasses at sites H and B.

demand is minimal, and midday, when atmospheric demand is at a maximum. During the predawn period, little or no transpiration occurs and xylem pressure potential moves toward equilibrium with soil matric potential. Xylem pressure potential typically reaches its lowest levels (most negative) in its diurnal cycle at midday between about 11 a.m. and 1 p.m., when the combination of high temperature and low humidity in the air results in the highest atmospheric demand for water vapor. This maximum atmospheric demand leads to increased transpiration rates, which results in the lowest plant water potential of the day.

Table 3. Correlation coefficients (*r* values) for drawdown and normalized cover repetition for major species at sites K and D, September 1986

[--, no data]

Cover	Site	
	K	D
Nevada saltbush	0.87	--
Rabbitbrush	.77	0.11
Greasewood	.73	-.90
Wild licorice	.85	--
Saltgrass	--	-.82
Alkali sacaton	--	-.12

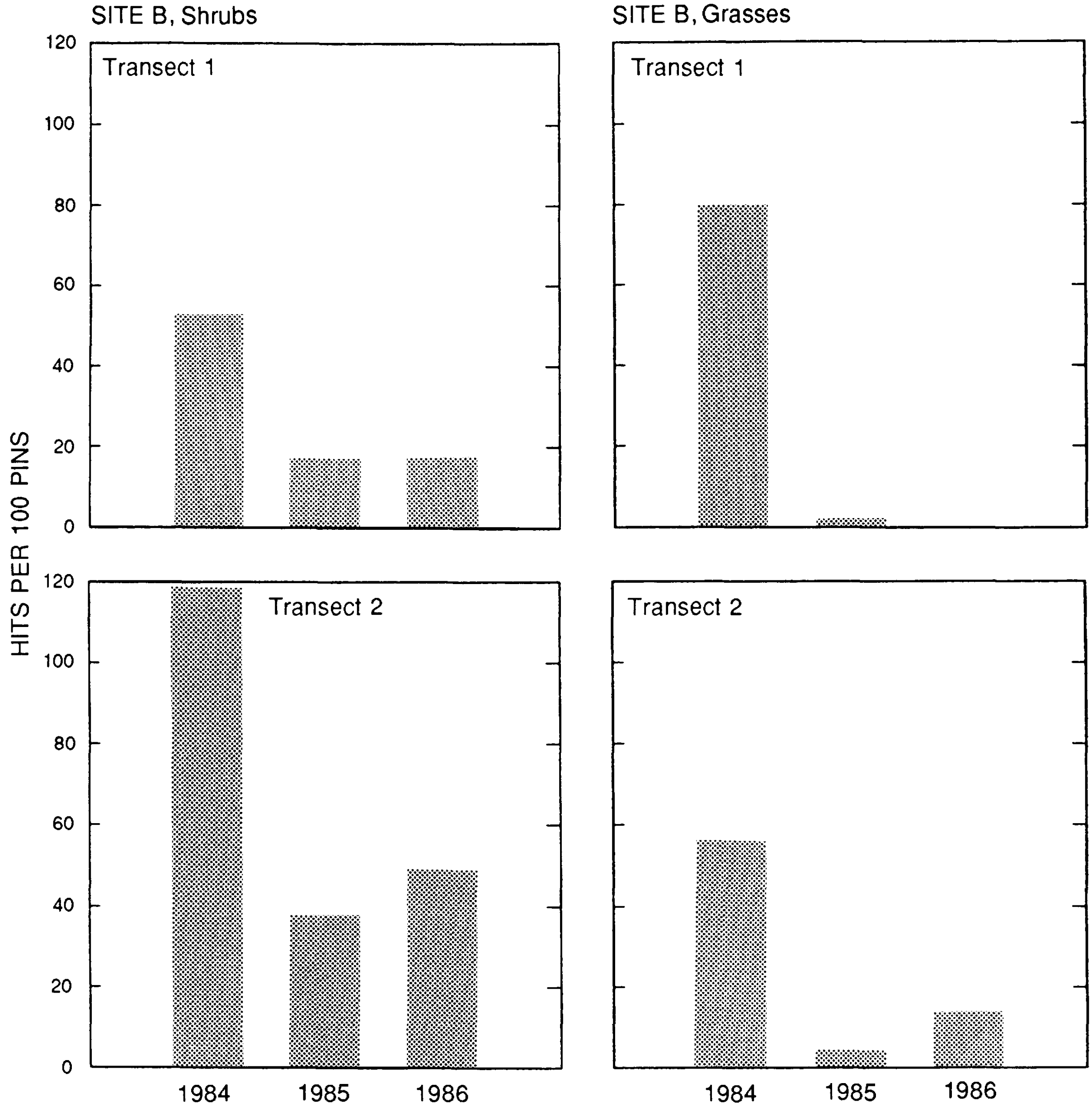


Figure 17. Continued.

Table 4. Specific conductance of saturated soil extracts for soil samples at each transect, October 1984

[Specific conductance, in microsiemens per centimeter. --, no data]

Depth (m)	Transect					Depth (m)	Transect					
	K1	K2	K3	K4	K5		D1	D2	D3	D4	D5	D6
0.1	58,400	6,810	15,100	2,620	4,410	0.1	371	1,140	388	754	19,600	658
.2	52,900	14,600	6,220	3,100	3,620	.2	422	4,760	5,050	1,340	10,100	619
.3	43,500	18,000	3,620	3,610	6,520	.3	2,780	2,620	8,310	2,280	7,120	603
.4	46,400	22,900	3,430	2,590	8,930	.4	2,030	7,860	7,810	1,900	2,520	733
.5	39,300	23,000	2,370	2,870	6,780	.5	1,790	5,410	9,720	2,010	1,210	1,060
.6	27,900	21,600	1,870	2,640	4,930	.6	2,500	5,620	15,200	3,450	947	1,580
.7	20,300	15,800	3,780	2,410	3,730	.7	2,390	5,050	10,200	3,210	870	1,490
.8	17,500	9,930	2,540	2,310	2,010	.8	1,330	5,030	11,700	2,850	1,210	1,940
.9	10,900	7,700	5,880	1,960	1,200	.9	2,140	4,630	16,900	1,220	482	1,850
1.0	12,600	4,860	2,490	2,470	1,120	1.0	3,030	3,930	15,900	771	416	2,470
1.1	7,430	3,400	1,890	3,410	1,120	1.1	2,710	4,860	16,200	618	791	3,180
1.2	6,670	2,930	2,360	3,840	1,420	1.2	2,540	2,370	18,300	628	608	5,650
1.3	4,830	2,260	994	3,430	1,800	1.3	2,270	4,440	12,100	780	416	4,560
1.4	2,580	3,010	1,320	1,290	1,290	1.4	1,920	5,770	4,850	570	543	3,020
1.5	2,430	4,180	3,220	757	1,300	1.5	1,760	5,180	5,030	439	776	3,040
1.6	--	2,780	1,950	676	1,530	1.6	1,670	5,980	4,100	359	822	2,400
1.7	5,150	1,350	1,760	763	769	1.7	1,600	5,810	2,130	392	737	1,870
1.8	1,610	2,180	2,330	740	1,020	1.8	1,320	4,360	2,390	657	1,920	2,120
1.9	4,800	--	3,350	764	698	1.9	1,040	3,940	2,680	380	707	1,660
2.0	1,670	2,140	2,000	603	615	2.0	866	3,770	2,300	607	1,310	1,650
2.1	478	966	1,330	550	523	2.1	687	3,590	1,870	--	633	1,380
2.2	998	1,510	1,750	583	584	2.2	644	3,190	2,090	--	--	1,080
2.3	3,820	767	1,750	640	--	2.3	693	2,960	1,580	--	--	984
2.4	1,130	797	2,140	790	--	2.4	541	2,160	1,900	--	--	--
2.5	--	995	2,530	--	--	2.5	557	2,190	1,380	--	--	--
2.6	5,400	1,100	2,160	--	--	2.6	--	2,020	1,070	--	--	--
2.7	3,280	632	1,780	--	--	2.7	--	2,480	964	--	--	--
2.8	--	1,060	1,750	--	--	2.8	--	2,010	1,930	--	--	--
2.9	--	1,300	730	--	--							
3.0	--	--	734	--	--							
3.1	--	--	620	--	--							
3.2	--	--	690	--	--							

Seasonal Variation

Changes in midday and predawn xylem pressure potentials over the growing season were analyzed by combining data for each species at all stations for the study period of 1984–86. Combining the plants from all stations masks much of the natural variability in xylem pressure potential within a given plant due to instantaneous weather conditions and physiological variability at the time of measurement. Monthly variability in midday and predawn xylem pressure potential for five plant species is summarized in figures 19 and 20. All data points used in the boxplots are mean values of xylem pressure potential taken from three branchlets at the time of measurement.

Table 4. Specific conductance of saturated soil extracts for soil samples at each transect, October 1984—*Continued*

Depth (m)	Transect			
	H1	H2	B1	B2
0.1	118,000	230,000	4,160	1,250
.2	78,400	10,330	4,120	1,220
.3	38,700	60,200	4,350	1,340
.4	36,700	40,400	3,010	941
.5	59,400	35,200	3,260	1,080
.6	40,800	36,700	2,160	1,293
.7	16,900	21,200	1,530	1,200
.8	9,030	--	697	1,900
.9	43,000	21,500	496	31,000
1.0	13,300	27,300	338	50,100
1.1	4,990	29,500	366	28,800
1.2	3,590	28,900	359	1,800
1.3	4,320	25,100	365	1,930
1.4	4,610	--	362	1,680
1.5	8,410	25,600	293	1,120
1.6	5,340	25,700	382	1,030
1.7	13,100	--	431	886
1.8	17,000	--	336	751
1.9	354	--	--	806
2.0	--	--	--	582
2.1	--	--	--	508
2.2	--	--	--	393

Midday and predawn xylem pressure potentials generally decreased from March or April through October. Midday potentials were the highest in April for rabbitbrush, although March was the highest month for the other species. The lowest xylem pressure potentials for rabbitbrush and greasewood were measured in August, after which they generally increased. Lowest potentials were measured during September in the other three species. The pattern of slight increases in xylem pressure at the end of the growing season reflects seasonal decreases in atmospheric demand and changes in plant phenology.

Relative monthly evapotranspiration estimated for study sites near Bishop shows that evapotranspiration begins decreasing in July and is low by October, indicating the beginning of the dormant winter period (Duell, 1990). Through most of the growing season, rabbitbrush had the highest xylem pressure potential of the species studied, and its variability in measured potential generally was least (fig. 19). By contrast, greasewood and sagebrush showed large seasonal variations. Median xylem pressure potentials in greasewood ranged from –2.4 MPa in March to –4.9 MPa in August, and sagebrush ranged from –1.8 in March to –5.8 MPa in September. Nevada saltbush was less variable in median xylem pressure potential during the growing season than greasewood and sagebrush, but Nevada saltbush had the lowest measured potential at the beginning of the growing season.

The seasonal variability in xylem pressure potentials is directly related to the plants' ability to adjust their cellular osmotic potential. These adjustments allow the plants to tolerate progressively lower xylem water potentials, extending their ability to transpire and extract water from increasingly dry soil. Dileanis and Groeneveld (1989) found that greasewood and Nevada saltbush are capable of osmotic adjustments to a much larger extent than rabbitbrush and sagebrush, and that Nevada saltbush maintains a low cellular osmotic potential from the beginning to the end of the season. The different ranges in seasonal variation of xylem pressure potential resulting from differences in degree of osmotic adjustment are clearly shown for greasewood (fig. 19). However, sagebrush has little capacity for osmotic adjustment, so the seasonal variability in xylem pressure potential must be accounted for by another mechanism.

Predawn xylem pressure potentials, although higher than at midday for all five species, continued to decrease throughout the growing season (fig. 20). In September and October, when the midday xylem pressure potentials increase as atmospheric demand decreases, the predawn potentials continue to decrease. This decrease seems to be due to the continued drying of the soil in the shallow rooting zones.

Variation in Predawn Xylem Pressure Potential with Changes in Soil Water Content

Correlation coefficients (*r* values) for the relation between predawn xylem pressure potential and θ (millimeters of water) in the top 1.5 m of the soil profile were calculated for sites H and B, as shown in table 5. Values for θ were derived from spring and late summer gravimetric measurements and from monthly neutron-probe measurements. At site H, rabbitbrush and greasewood show a strong correlation in 1985 (r>0.9) and a moderate correlation in 1986. The difference in the results of this analysis between these two years probably is the result of the high salt content in the upper soil profile at this site. Soil water content in the upper soil profile increased in 1986 due to increased precipitation that year (fig. 12). Although the soil contained more water, its availability to the plants may have been limited by its high salinity. Nevada saltbush shows a negative correlation with θ at site H, indicating that some factor other than θ was affecting the predawn xylem pressure potentials. At site B, in 1985 and 1986, *r* values greater than 0.9 for rabbitbrush and greasewood show a strong positive correlation between predawn xylem pressure potential and θ. As θ progressively decreased through both growing seasons, predawn xylem pressure potential also decreased.

Variation Between Transects

Variation in xylem pressure potential for midday measurements of Nevada saltbush was mostly between 3 and 4.5 MPa at all transects where this species was present (fig. 21). At site K, midday pressure potentials varied little among the transects along the drawdown gradient away from the pump-equipped wells. Distribution of the data was different between years. The median of xylem pressure potentials was much higher in 1985 than in 1984 or 1986, ranging from –2.95 to –3.50 MPa. In 1984 and 1986, the median values ranged from –3.75 to –4.45 MPa. The reason for these differences is unknown. Differences between 1985 and 1986 predawn xylem pressure potentials (fig. 22) in Nevada saltbush at site K are much less than for the midday measurements,

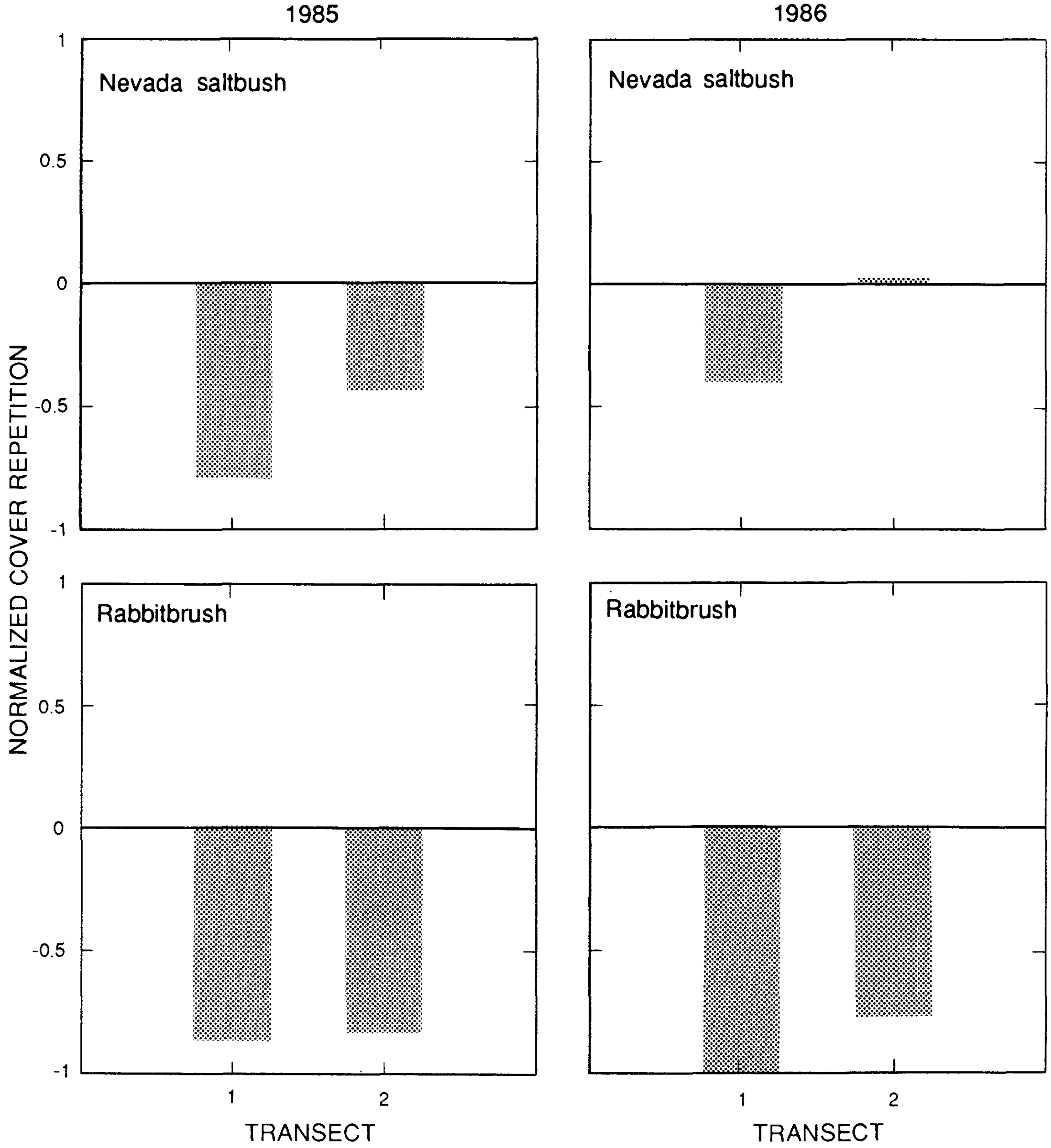


Figure 18. Normalized cover repetition for individual species at site B measured in September 1985 and 1986. Transect 1 underwent drawdown, transect 2 is control transect.

although the median value was less in 1985 than in 1986 at all transects except K3.

Differences in midday xylem pressure potentials of Nevada saltbush between transects B1 and B2 and between transects H1 and H2 were small (fig. 21). The largest differences occurred in 1984, when the control transects had lower pressure potentials than at the drawdown transects. Measurements of predawn xylem pressure potential (fig. 22) at sites H and B have similar median values between the drawdown and control transects in 1985 and 1986. In 1986, the plants at both site B transects had a much larger range of xylem pressure

Table 5. Correlation coefficients (*r* values) for relation between predawn xylem pressure potential and soil water content in top 1.5 meters of soil profile at sites H and B, 1985–86

Site	Year	Nevada saltbush	Rabbitbrush	Greasewood
H	1985	-0.53	0.91	0.99
	1986	-.41	.77	.59
B	1985	.36	.95	.99
	1986	.77	.95	.94

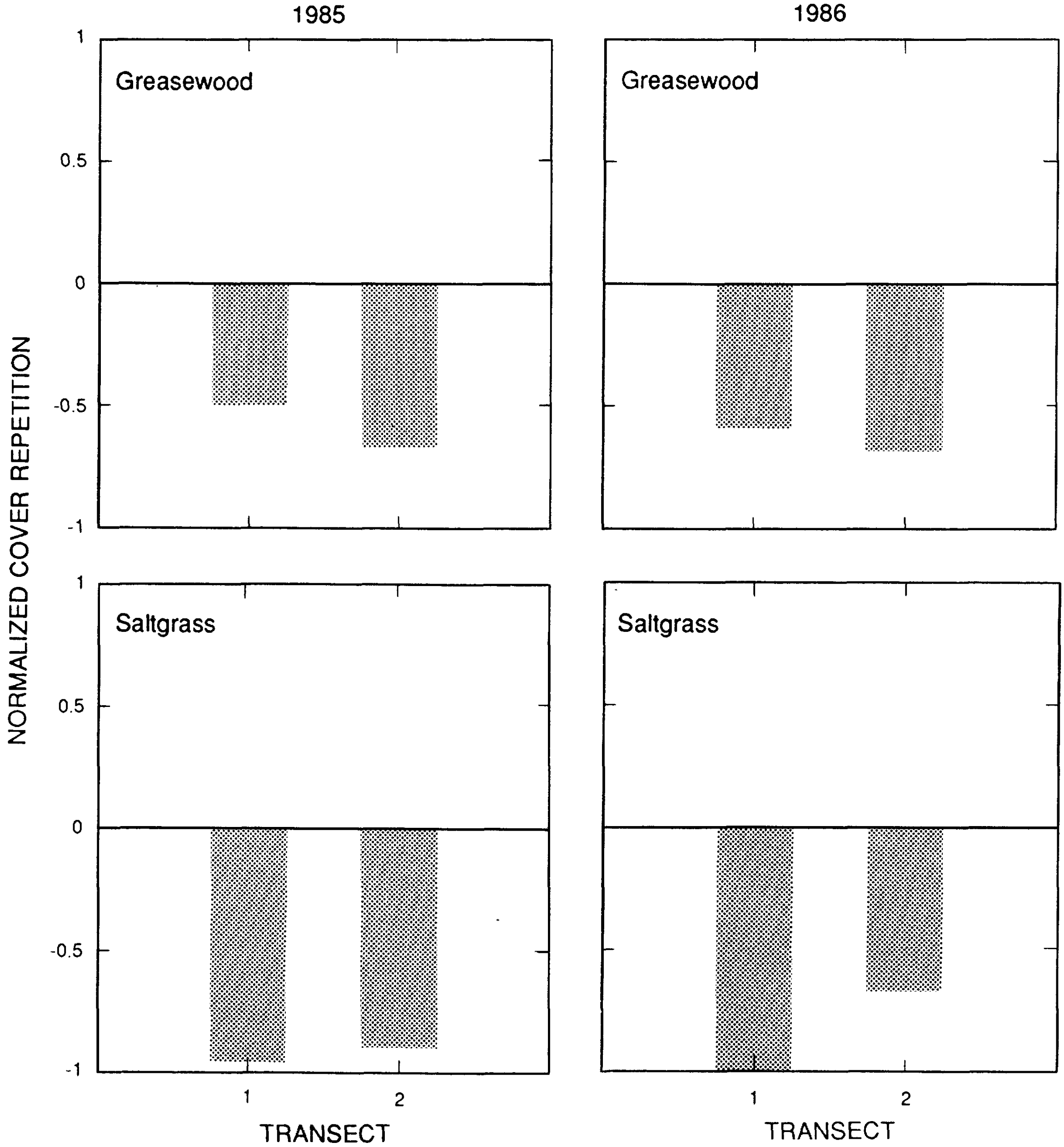


Figure 18. Continued.

potentials than those at other sites. The measurements that make up the upper part of the distribution were taken late in the growing season when soil water was at a minimum. This large range of pressure potentials may be due to limited soil water available in the late season; however, this is not likely because both transects showed the same reaction and because soil profiles of θ and soil ψ_m do not indicate limiting soil water conditions.

Measurements of midday xylem pressure potential for rabbitbrush showed very little variation between transects or between years (fig. 21). At sites K and D, the median values and the distribution of data increased or decreased slightly along the cone of water-table drawdown, but no trend attributable to the water table was apparent. Little difference existed in measurements of midday pressure potential between transect H1 and its corresponding control transect (H2) during 1984–86. There were differences between transects B1 and B2 during 1985. Xylem potentials were distinctly lower at the drawdown transect (B1) than at transect B2, probably reflecting the stress that caused the large decrease in rabbitbrush on this transect during 1985. In 1986, little difference in midday xylem pressure potentials existed between transects B1 and B2 because of the greater soil water available from heavy winter rains and the decrease in vegetative cover from 1985.

Predawn xylem pressure potentials (fig. 22) for rabbitbrush showed no increasing or decreasing trend between transects. The exception to this was at site B where in 1985, as with the midday measurements, predawn xylem pressure potentials were notably lower at transect B1 than at B2. The variability of the data also was greater at transect B1 than at any other site during 1985. During 1986, pressure potentials at transect B1 again were lower than at B2, but the differences were less because potentials at B2 generally were less than they were in 1985. As was the case with Nevada saltbush, soil water seemed to be limited at transect B2, as well as at transect B1, based on the predawn measurements of xylem pressure potential.

Greasewood undergoes a large seasonal variation in predawn and midday xylem pressure potentials; therefore, comparison of boxplots from one transect to the next was more difficult than it was for other species. Figure 21 shows that although midday xylem pressure potentials between transects vary, the variation does not seem to be related to the artificially created water-table drawdown. Midday xylem pressure potentials at transect B2 for greasewood were most variable from 1984 through 1986 and had the lowest median of any of the transects during 1984. The median xylem pressure potential at transect B2 increased to 3.2 MPa in 1985, the third highest median of the transects measured. In 1986, the median decreased again to near the level of 1984. Why this decrease would happen at a site with minimal drawdown effects and why the highest median pressure potentials occurred during the driest year of the three is unknown.

During 1986, there seemed to be a trend toward decreasing xylem pressure potentials closer to the pumped wells at site D. The exception to this trend was transect D1, which had a higher median value than any of the other transects at site D. Operation of the pumps and leaks in the discharge lines, or other local ground disturbances at this site, could have caused different soil water conditions in this area than at the other transects. Because 1986 was the only full season of water-table drawdown at this site, this trend of decreasing potential with deeper water tables likely would have continued in subsequent years and perhaps would have created the range of plant stress that was the objective of the study.

Predawn xylem pressure potential measurements showed no consistent relation to the water table except at site B, where in 1985 and 1986 the median pressure potential was lower at transect B1 than at any other transect (fig. 22). The range of predawn pressure potentials also was large (particularly in 1986), indicating that greasewood is adaptable to a large range of soil water conditions.

Plant Growth

Measurement of growth of most shrubs under field conditions is difficult. Measurements of plant growth in Owens Valley indicated that the amount of growth of various branches of an individual plant varied greatly during a season. Greasewood was particularly a problem because some shoots grew more than 500 mm during the growing season, whereas the more typical shoots grew only 30 to 100 mm. For this study, all side and terminal branches distal to a point marked with a color-coded electrical wire on each of three branches of selected shrubs were measured. Shoots that were marked for measurement were carefully selected by experienced observers in an attempt to select as representative a set of measured branches as possible. Repeat measurements showed that certain side branches grew little, if at all, during the growing season. To avoid this effect and such things as midseason death of branches and broken branch tips, the length of the longest shoot on each color-coded branch was measured and averaged for each sampling date. Nevertheless, such things as branch-tip shrinkage, breakage, and predation from animals sometimes resulted in apparent negative growth late in the growing season.

Response to Precipitation

In reviewing the data on plant growth during 1983–86, a large variation in growth from year to year in Nevada saltbush and rabbitbrush was measured. Growth of greasewood, by contrast, was much less varied from year to year. These annual changes in growth seem to be independent of the depth of the water table—changes were positive and negative and occurred at all study sites. There was a close correlation between total annual (November through October) precipitation at the established weather station nearest the study sites and the average annual shoot growth of rabbitbrush at all transects at site D and of Nevada saltbush and rabbitbrush at all transects at site K (fig. 23). Correlation was not apparent between precipitation and growth of greasewood at these two sites. The fast-drawdown sites were used for this analysis because the plants seemed to be less affected by water-table drawdown than at the slow-drawdown sites. Furthermore, each fast-drawdown site had five or six transects with plant-growth measurements that minimized growth differences among individual plants. Growth variation in response to precipitation was much greater at site D than at site K, probably as a result of soil texture at the two sites. Nearly all the precipitation was absorbed by the sandy soil at site D. In contrast, the soils at site K are fine textured, resulting in little infiltration from the surface. As a result, θ in the shallow rooting zone is more directly affected by precipitation in the areas that have sandy soils.

Response to Changes in Depth to Ground Water

Effects of lowered water tables on plant growth are most apparent in data from site B. The two transects at this site had the greatest vegetative cover of all study transects in the Bishop Basin. Growth of the three major shrub species at transect B1 during 1984, before pumping, was similar to growth at transect B2 (fig. 24). Greasewood grew slightly more at transect B2 than at B1. During 1985, after the water table had been drawn down about 1.8 m, growth of Nevada saltbush and rabbitbrush at transect B1 was greatly reduced compared with transect B2, the control transect. For these two species, not only was the total amount of growth less, but growth stopped earlier in the year at transect B1 than it did at the control site (B2). For example, growth of Nevada saltbush stopped by mid-June at the drawdown site, but continued until late July at the control site. Growth measurements were not taken from rabbitbrush after early July because the three marked branches were dead. Growth of greasewood was similar at transects B1 and B2 during 1985.

Growth during 1986 was greater at transects B1 and B2 than it was in 1985. Rabbitbrush grew slightly more at the control site than at the drawdown site, but growth of the other two major shrubs was similar. These data show that growth of the three major shrubs in 1986 was not limited by water-table drawdown. The overall greater growth at these two transects probably is due to the greater than normal precipitation during the winter of 1985–86. In addition, because of a decline in rabbitbrush during 1985, more soil water was available to the remaining vegetation.

At site H, comparisons between the drawdown transect (H1) and the control transect (H2) (fig. 25) are a little less reliable than at site B because the water level at the control transect declined throughout the study, either because of the effect of the pump-equipped wells or because of a general decline in the water table in that area. The water table declined from a depth of about 0.3 m at the beginning of pumping to more than 2 m by October 1986 at transect H2. The record of water-table depths under transect H2 is poor because the observation well was only 1.5 m deep and was dry throughout most of the pumping period. However, the water table at the drawdown site was consistently lower than the control site, where auger profiles to the water table showed water tables ranging from 1 to 2 m. During 1984 and 1986, the growth of Nevada saltbush was greater at the control site than at the drawdown site. The trend was just the opposite during 1985. The reasons for the greater growth of Nevada saltbush at the drawdown site are that the shrub selected for measurement in 1985 was near the edge of the exclosure and had anomalously large growth, as a result of the perimeter effect discussed earlier in this report. In addition, growth of Nevada saltbush at the control site was low because of a heavy infestation of leaf beetles (*Chrysomela* sp.) in July 1985. The plant selected for measurement in 1986 was near the center of the exclosure and was not subject to the perimeter effect.

Growth of rabbitbrush was similar at the two transects at site H in 1984 and 1985, but the measured bush at the control site showed more growth during 1986 than the one at the drawdown site. The increased water-table drawdown under transect H1 in 1986 may have accounted for this difference.

Greasewood grew longer shoots at the drawdown transect than at the control transect in all three years of the study. The water-table decline may have improved the rooting conditions for greasewood by increasing the supply of oxygen in spaces previously occupied by water. The fact that greasewood does not grow in frequently flooded sites (Branson and others, 1970) indicates that these plants require well-oxygenated soil in the rooting zone.

Variations in growth at the fast-drawdown sites K and D showed no correlation with depth to water along the cone of depression created by the pump-equipped wells. Differences in total shoot growth between transects at sites K and D seemed to be the result of the natural variation in growth rates. Growth of Nevada saltbush at transects K1–K5 (fig. 26) shows that the greatest growth during 1984–86 was at transect K1, which was closest to the pump-equipped wells and therefore had the greatest water-table drawdown. The next greatest amount of growth was at transect K5, which was not affected by artificial drawdown. The transects that were intermediate in distance from the pumped wells had the least growth in all three years.

Phenological Stages

Many plants undergo a seasonal life cycle that takes them from winter dormancy through leaf growth, flowering, and seed production. In desert areas, this cycle is closely related to water availability. Plants produce new leaves, grow, and reproduce after seasonal periods of rainfall. The quantity and duration of the rainfall usually have an effect on the timing and amount of leaf growth and seed production. To determine normal cycles of phenological development and to see if these cycles were altered by water stress induced by lowered water tables, phenological stages of the shrub species studied were observed and recorded at each vegetation sampling site on each sampling date. The following eleven phenological stages were recognized in these shrubs:

0: dormant (spring) (a continuation of autumn dormancy)
1: beginning leaf growth
2: one-half leaf
3: three-fourths leaf
4: full leaf growth
5: flower stalks or buds visible
6: early bloom
7: full bloom
8: late bloom—early seed formation
9: seed ripe
10: seed shattering or disseminating
11: dormant (autumn)

Phenological changes in 1985 for Nevada saltbush, rabbitbrush, and greasewood at sites B, D, H, and K (fig. 27) show that greasewood develops earliest, Nevada saltbush is intermediate, and rabbitbrush is the latest to complete the phenological cycle. This is the same order of relative drought tolerance as indicated by osmotic adjustment (Dileanis and Groeneveld, 1989) and by seasonal changes in xylem pressure potential. Because rabbitbrush does not complete reproduction until after October, it requires water for a much longer period of time than does greasewood, which starts going into dormancy in September. The rate of phenological change in greasewood and Nevada saltbush varied little between the Bishop and Owens Lake Basins. Rabbitbrush in the Bishop Basin (sites D and B) was at a lower phenological stage than the same species in the Owens Lake Basin (sites K and H) throughout most of the growing season. This is perhaps indicative of a longer growing season in the Owens Lake Basin, with growth and phenological development starting earlier than in the Bishop Basin.

The only species that seemed to show a phenological response to water-table lowering was greasewood at site B in 1986 (fig. 28). Developmental stages occurred earlier at transect B1 than at B2, probably in response to reduced water availability. Differences in developmental stages of rabbitbrush or Nevada saltbush were not seen between transects B1 and B2. Judging from the presumed drought tolerances of these three species, greasewood would be the least likely to show a phenological response between the drawdown and control transects.

SUMMARY AND CONCLUSIONS

In arid lands, the quantity of soil water available commonly is the limiting factor to the growth and survival of plants. In most arid regions, soil water is derived almost exclusively from precipitation, and plants adapt to normal variations in precipitation quantity. Owens Valley is different from most arid regions in that, although it normally has a small amount of seasonal rainfall, a shallow water table underlies much of the valley. Water from this shallow water table subirrigates the soil zone within 1 to 2 m of the water table, providing soil water to the plants. The present study indicates that subirrigation from the shallow water table provides some water to the plants, but the water table primarily functions as a water bank to the plants, which may be critical to the plants' survival only when water from precipitation that infiltrates from the surface is inadequate.

The plant population and soil water system studied in Owens Valley is similar in some respects to that in other desert environments without a shallow water table. Both systems have a predominance of roots in the shallow soil zone, where most infiltration from precipitation occurs, distinct physiological mechanisms for drought tolerance or avoidance, and a seasonal growth and reproduction cycle controlled largely by the quantity of water available from precipitation. Plant communities in Owens Valley are different from those in other desert areas because they have access to the water bank provided by subirrigation from the shallow water table. Roots, extending into this soil zone containing capillary water, supplement the water extracted from the shallow soil zone by the largest mass of roots and allow continued extraction of water when precipitation is inadequate.

When considering management of the plant communities in Owens Valley, the most important consideration is maintaining water availability in the zone that would be drained by water-table drawdown. When a water table declines, water drains from the soil by gravity, leaving behind an amount of residual water in the former capillary and saturated zones that is determined by the textural characteristics of the soil. This stored water then is available to the plants if they need to grow their roots into this zone. However, because the source of this water has been removed by the lowered water table, it usually is not replenished once used by the plants. Stored water can be replenished by exceptionally heavy rainfall that causes unusually deep infiltration of water or a rise in the water table. The plants must grow roots deeper into the drained soil to reach more water as the soil profile dries. The present study showed that the plants, particularly in the fine-textured soils in the Owens Lake Basin, did grow roots deeper to reach the stored water in the deeper soil zones. How deep the plants can grow additional roots to reach deeper water is uncertain. In soils with coarser textures and correspondingly less water-holding capacity, the stored water is depleted more rapidly and therefore provides a much smaller bank of water to function as a buffer for the plants against water-table drawdown.

In this project, we were not able to test completely the ability of the plants to adapt to changes in ground-water level because not enough drawdown was produced by the pump-equipped wells, and the pumping was not of sufficient duration to test long-term reactions of the plants. At site K, water-table drawdown was shallow enough that the plants easily grew roots into the newly drained soils during the three seasons of pumping. The deeper roots grew into the zone of capillarity, and thus it would be unlikely that these plants would show long-term effects of the drawdown achieved. The soil at site K was fine textured and therefore held a large bank of water when the drawdown occurred. It can be postulated, although not proved with this study, that this large bank of water could sustain the vegetation for some period of time, even if the water table was drawn down past the physical limits of rooting depth. The amount of time would be variable (possibly several years), depending on the amount of water available from precipitation. At site H, soil was fine textured as it was at site K to a depth of about 2 m. The 2-m-thick coarse sandy soil below 2 m had low water-holding capacity and hydraulic conductivity when drained to field capacity. Subirrigation from the ground water, which was drawn down below this layer, was minimal. The plants at this site grew their roots into the coarse sandy soil and used the stored water.

The coarse-grained, sandy soils in the Bishop Basin retain a much smaller bank of water after water-table drawdown than those at sites K and H. Plants in these areas are much more susceptible to stress from water-table drawdown. When ground-water levels are not influenced by pumping, the effects of a dry winter or a series of dry winters are buffered by the subirrigation from the water table. Water-table drawdown of 1.8 m at site B beginning in autumn 1984 corresponded with a drier than normal winter. The combination of the lack of precipitation and the small amount of stored water left in the newly drained soil was insufficient to sustain all the vegetation during the summer of 1985. Most of the rabbitbrush at transect B1 died in late 1985, but Nevada saltbush and greasewood were not affected greatly. The plants grew additional roots into the newly drained soil at this site. Rabbitbrush apparently did not grow its roots enough to get to the deeper water, as was the case at sites K and H in the Owens Lake Basin. Its demise probably was due to the lack of water available in the upper zones at site B. The winter of 1985–86 was relatively wet and that, along with decreased plant cover at transect B1, allowed the remaining plants to survive without apparent stress and without further decline in cover during the summer of 1986. If pumping had continued for several more years, plants remaining at this site likely would have sustained about the same density as in 1986 (subject to changes caused by variations in precipitation) because the roots had grown deep enough to remain in contact with the zone of capillarity that enables these plants to obtain water during seasons of decreased precipitation.

Site D was the only drawdown site where water tables were drawn down far enough to expect isolation of the rooting zone from the zone of capillarity. Pumping at this site was not of sufficient duration to have caused any major effects on the vegetation. Although soil texture at this site was similar to site B, the vegetative cover was much less, the prepumping water level was deeper, and several of the shrubs common along the transects were plants (such as shadscale) that generally are not considered to be phreatophytic. When the water table was drawn down, there was less vegetation presumably requiring less soil water; therefore, the quantity of precipitation that occurred was sufficient to sustain the plants through the two summers the pumps operated. The relatively wet winter of 1985–86 provided enough water so that the plants did not require a substantial supplement from the stored soil water. During the summer of 1986, the plants at transect D3 did grow roots deeper into the soil profile as shown by increased ψ_m below 1.5 m, but the plants at the other transects showed no apparent reaction to the drawdown. The zone of finer textured soil from about 1.5 to 3.5 m under the three transects closest to the pumping wells served as a buffer against water-table drawdown and a succession of dry precipitation years because of the large volume of water stored. If pumping had continued for several more years at this site and if these years coincided with low precipitation years, the phreatophytic plants at this site likely would have been affected adversely.

Several factors are important as indicators of individual or community plant stress in Owens Valley. The most important soil factor is the soil ψ_m. A soil ψ_m of 4.3 pF is the maximum attained at a depth greater than 0.5 m at nearly all the vegetation transects. This value, which usually occurred at a depth of about 1 m in the area of maximum root density, seems to be the maximum pF that these plants can achieve before they are stressed significantly. The only transect that had a soil ψ_m higher than 4.3 pF at depths greater than 0.5 m was transect B1. At this transect, soil ψ_m reached 4.6 pF about the time most of the rabbitbrush died in 1985. Plants apparently extract water only in the range greater than 4.3 pF when sufficient water is not available deeper in the soil profile. The maximum attainable soil ψ_m decreases with depth because of decreasing root densities, so the critical ψ_m decreases from 4.3 pF with depth in a soil profile.

The most indicative physiological measurement relating to water stress in plants is the predawn xylem pressure potential as measured by the pressure chamber. Midday measurements of xylem pressure potential are more negative than predawn measurements, but because they are so dependent on immediate atmospheric demand at the time of measurement, comparison of one measurement with another is difficult. Predawn measurements are made under more stable atmospheric conditions and are more indicative of the plants' water status with respect to the soil. Unusually low predawn measurements are indicative of internal plant stress and would be the best single measurement to monitor plant stress at a particular site.

The results of this study were limited by the lack of drawdown achieved at all of the drawdown sites, except site H. The less than desired drawdown was the result of a combination of undersized and underproductive wells and pumps, estimates of transmissivities that were too high, and stronger than anticipated upward hydraulic gradient through the confining layers. Obtaining the desired 9 m drawdown at site K may have been impossible, even with more wells, without considerable pumping to relieve pressure from the confined aquifer. The desired 9-m drawdown at site D required larger capacity wells than were installed. The other important aspect of this study that limited the results was the short duration of the pumping. The results obtained indicate that effects of water-table drawdown are affected greatly by the quantity and timing of seasonal precipitation. With enough rainfall, the plants at sites B and D need little water from subirrigation. In order to better evaluate the effects of any quantity of water-table drawdown, the plants need to be observed during dry, average, and wet years. Some effects would be observable only after a succession of dry years. This is true particularly of the plants in the Owens Lake Basin, where the fine-textured soils provide a considerable quantity of stored water within reach of the plant roots.

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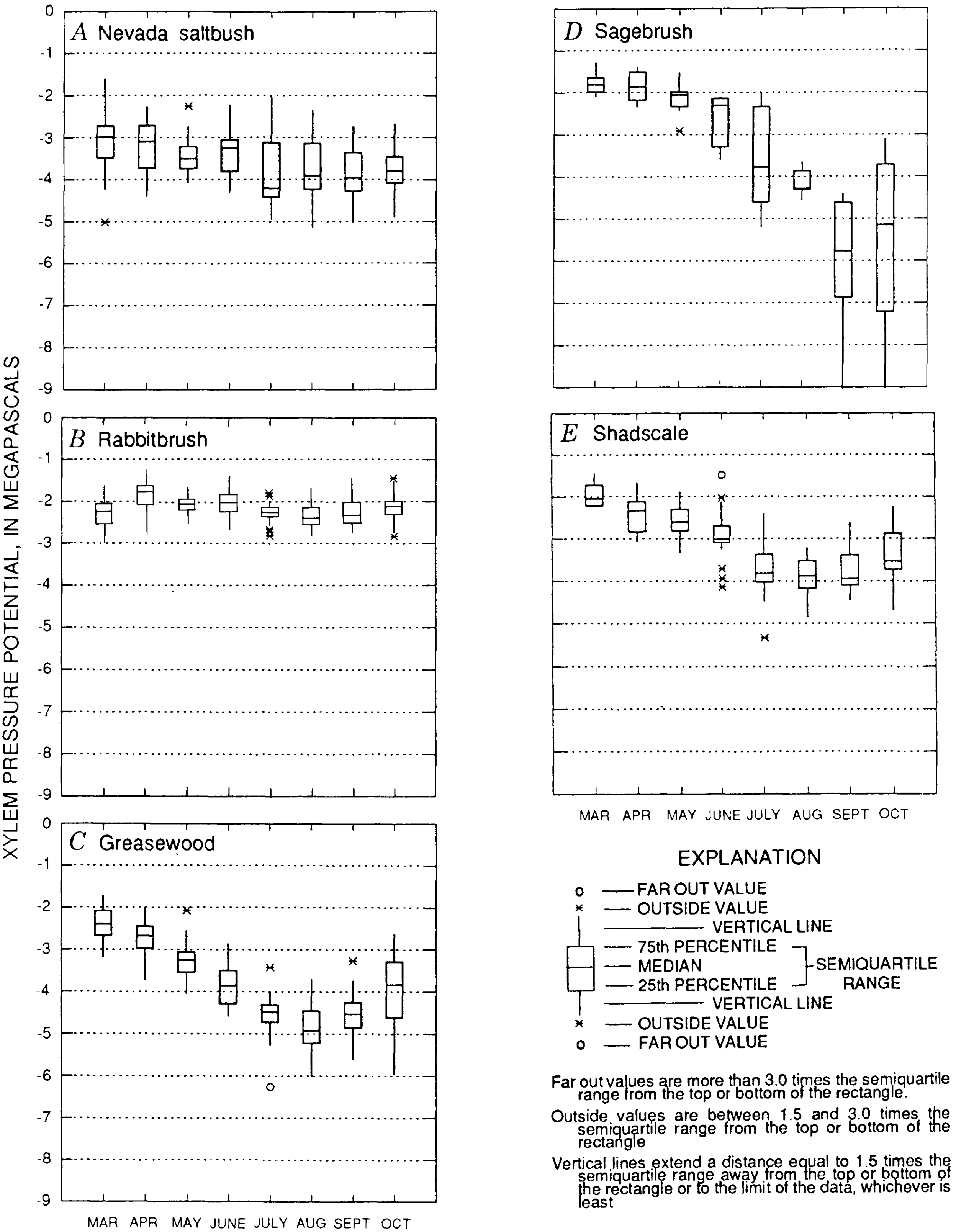
FIGURES 19–28

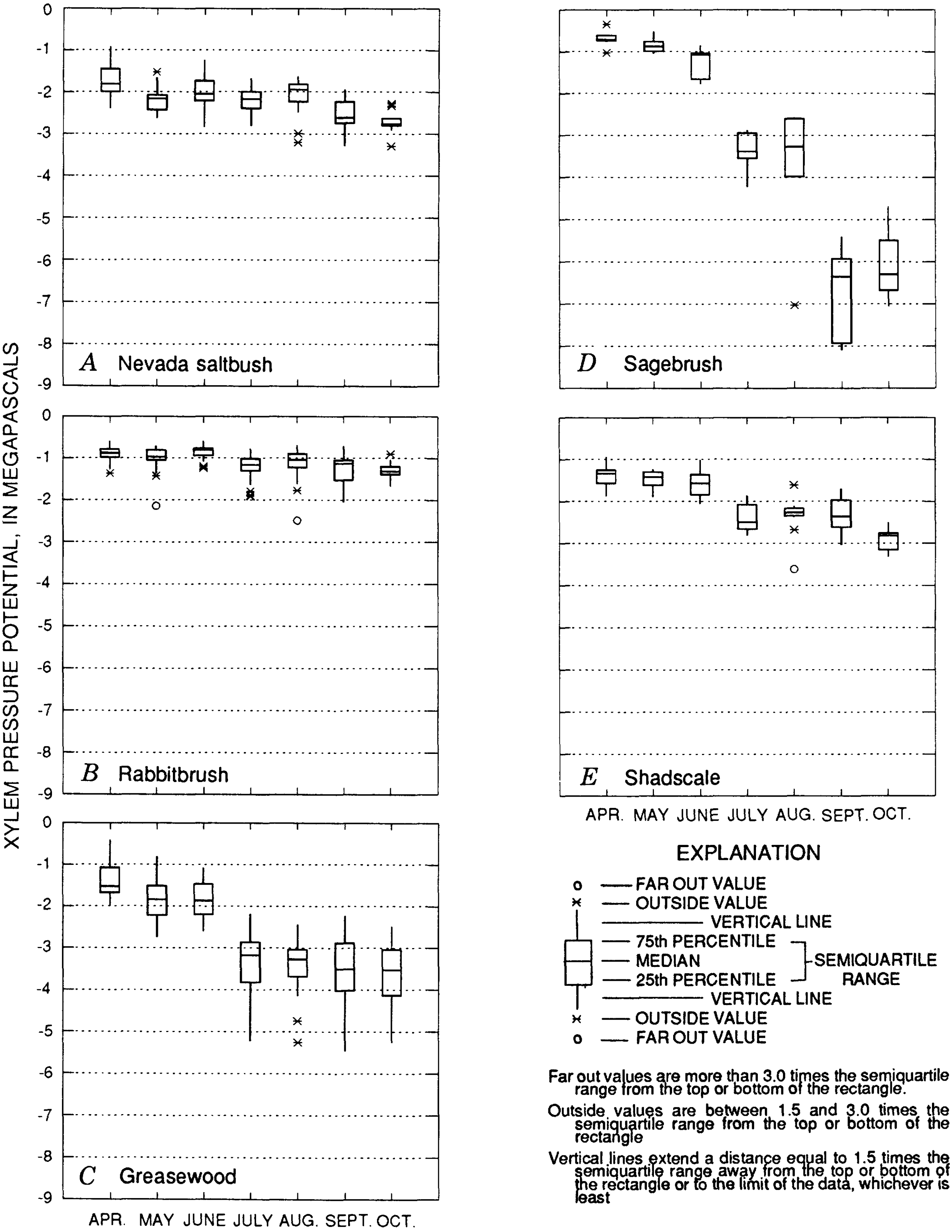


Far out values are more than 3.0 times the semiquartile range from the top or bottom of the rectangle.

Outside values are between 1.5 and 3.0 times the semiquartile range from the top or bottom of the rectangle

Vertical lines extend a distance equal to 1.5 times the semiquartile range away from the top or bottom of the rectangle or to the limit of the data, whichever is least

Figure 19. Midday xylem pressure potential by month for (*A*) Nevada saltbush, (*B*) rabbitbrush, (*C*) greasewood, (*D*) sagebrush, and (*E*) shadscale. Plots are combined data for all vegetation transects for 1985–86. (Schematic plots after Tukey, 1977.)



Far out values are more than 3.0 times the semiquartile range from the top or bottom of the rectangle.

Outside values are between 1.5 and 3.0 times the semiquartile range from the top or bottom of the rectangle

Vertical lines extend a distance equal to 1.5 times the semiquartile range away from the top or bottom of the rectangle or to the limit of the data, whichever is least

Figure 20. Predawn xylem pressure potential by month for (*A*) Nevada saltbush, (*B*) rabbitbrush, (*C*) greasewood, (*D*) sagebrush, and (*E*) shadscale. Plots are combined data for all vegetation transects for 1985–86. (Schematic plots after Tukey, 1977.)

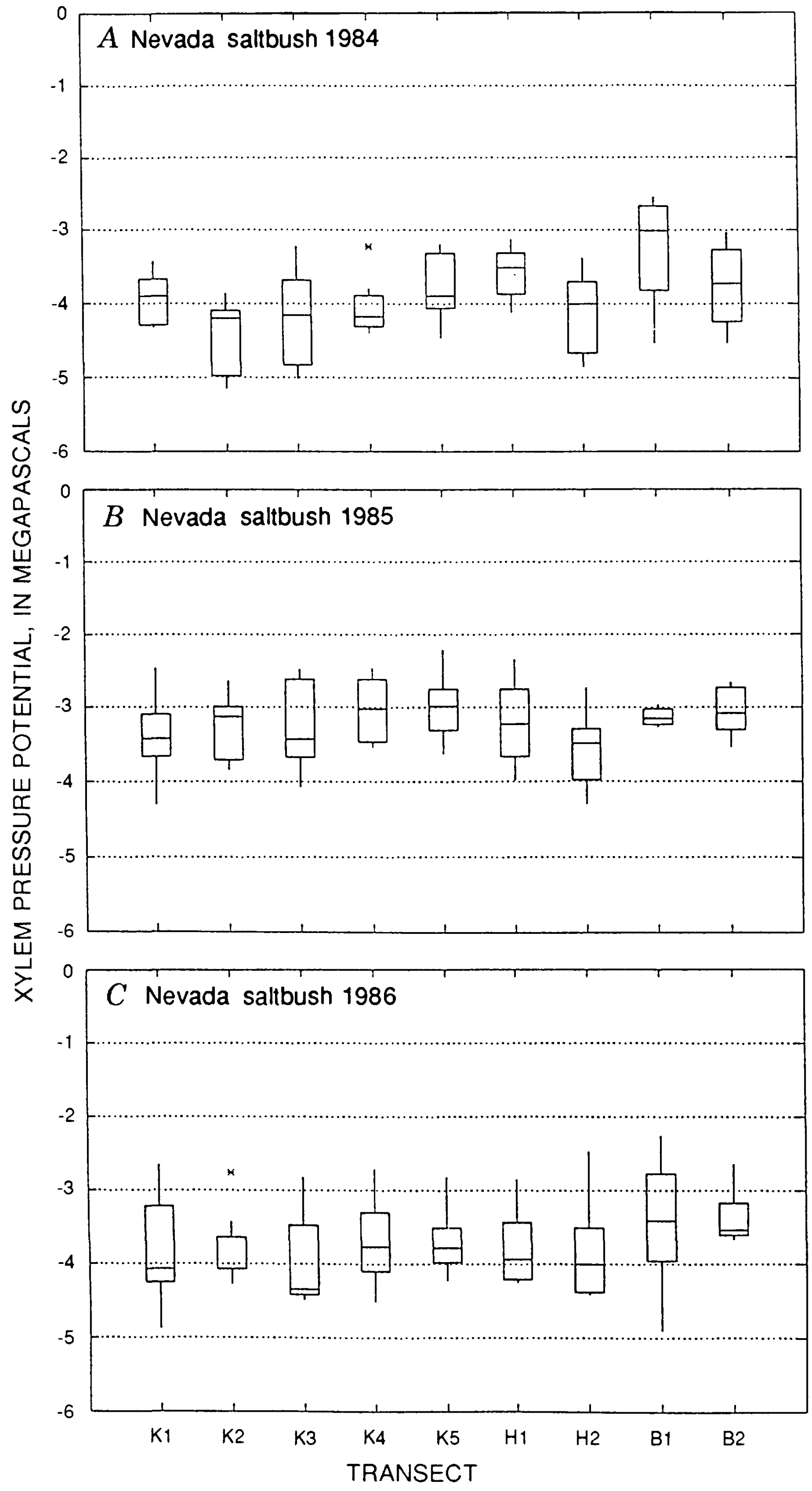


Figure 21. Midday xylem pressure potential at all vegetation transects. Plots show data for Nevada saltbush, rabbitbrush, and greasewood for 1984, 1985, and 1986. See figure 19 for explanation. (Schematic plots after Tukey, 1977.)

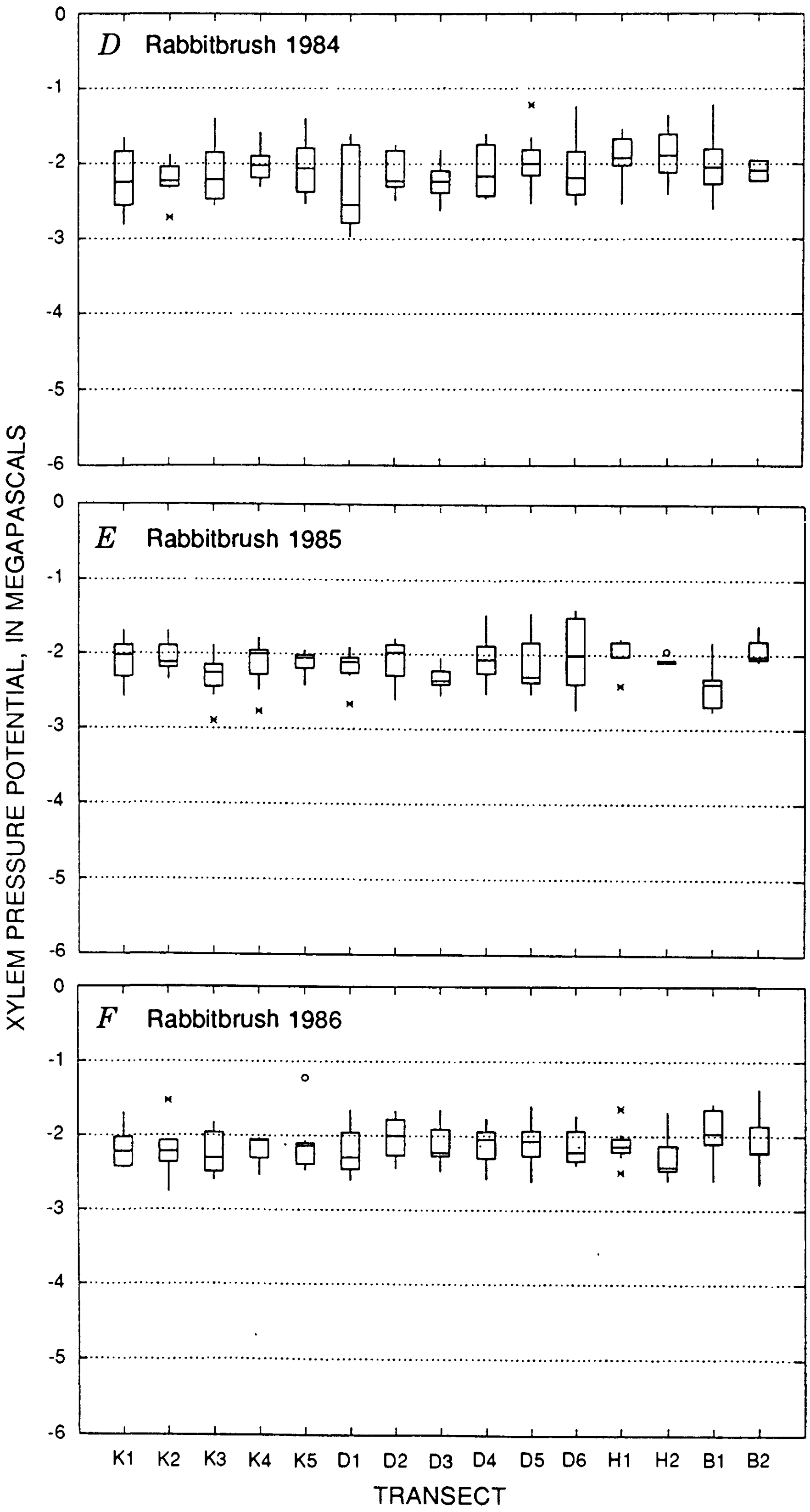


Figure 21. Continued.

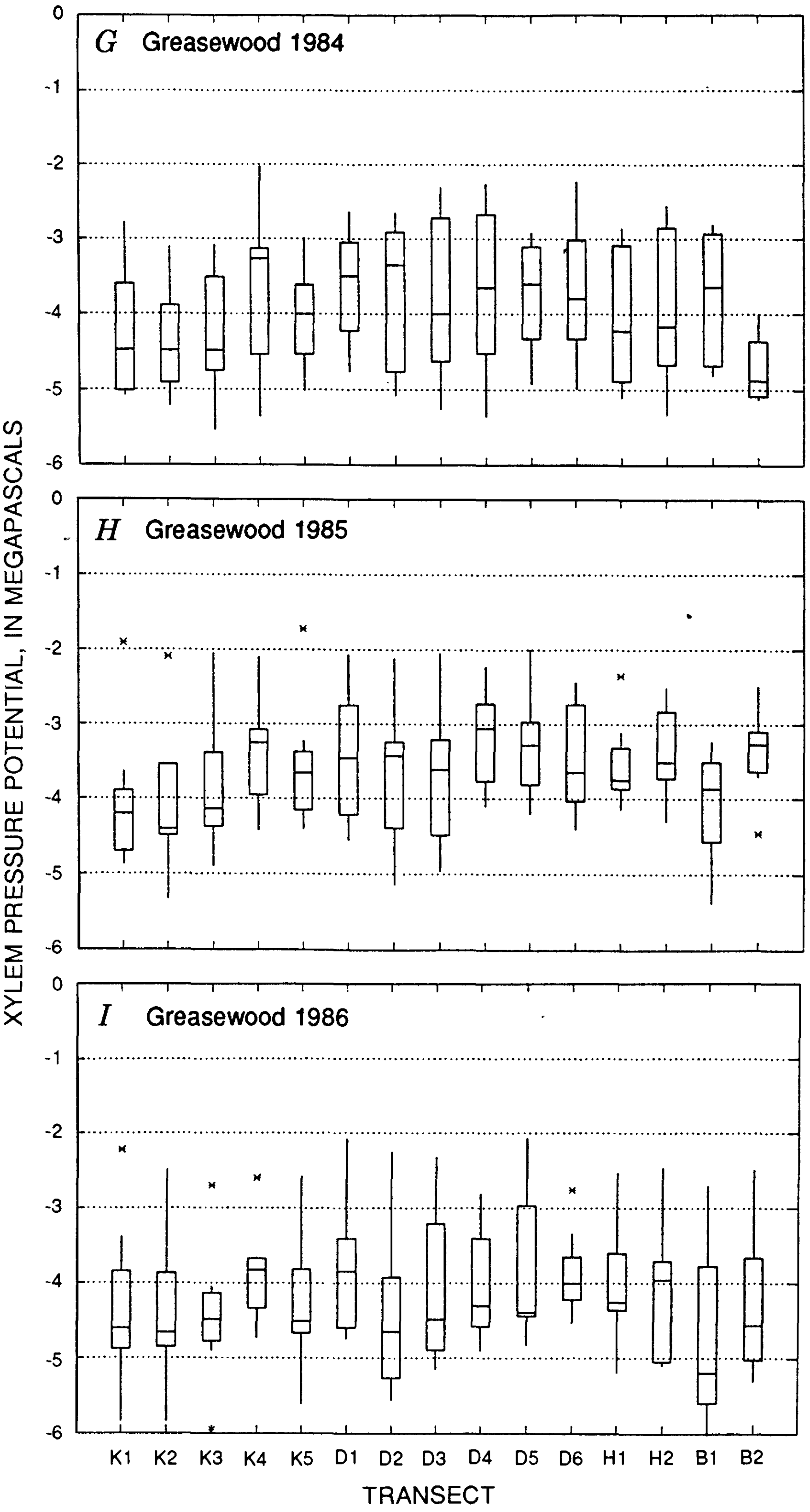


Figure 21. Continued.

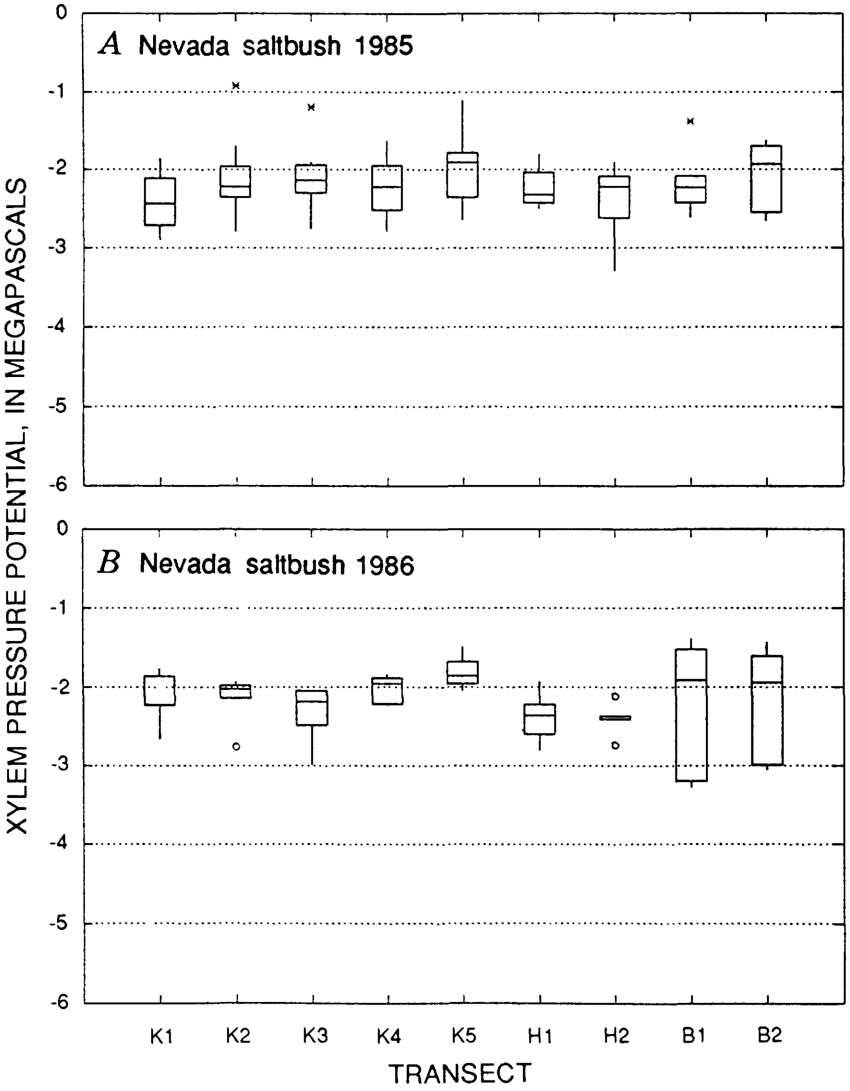


Figure 22. Predawn xylem pressure potential at all vegetation transects. Plots show data for Nevada saltbush, rabbitbrush, and greasewood for 1985 and 1986. See figure 19 for explanation. (Schematic plots after Tukey, 1977.)

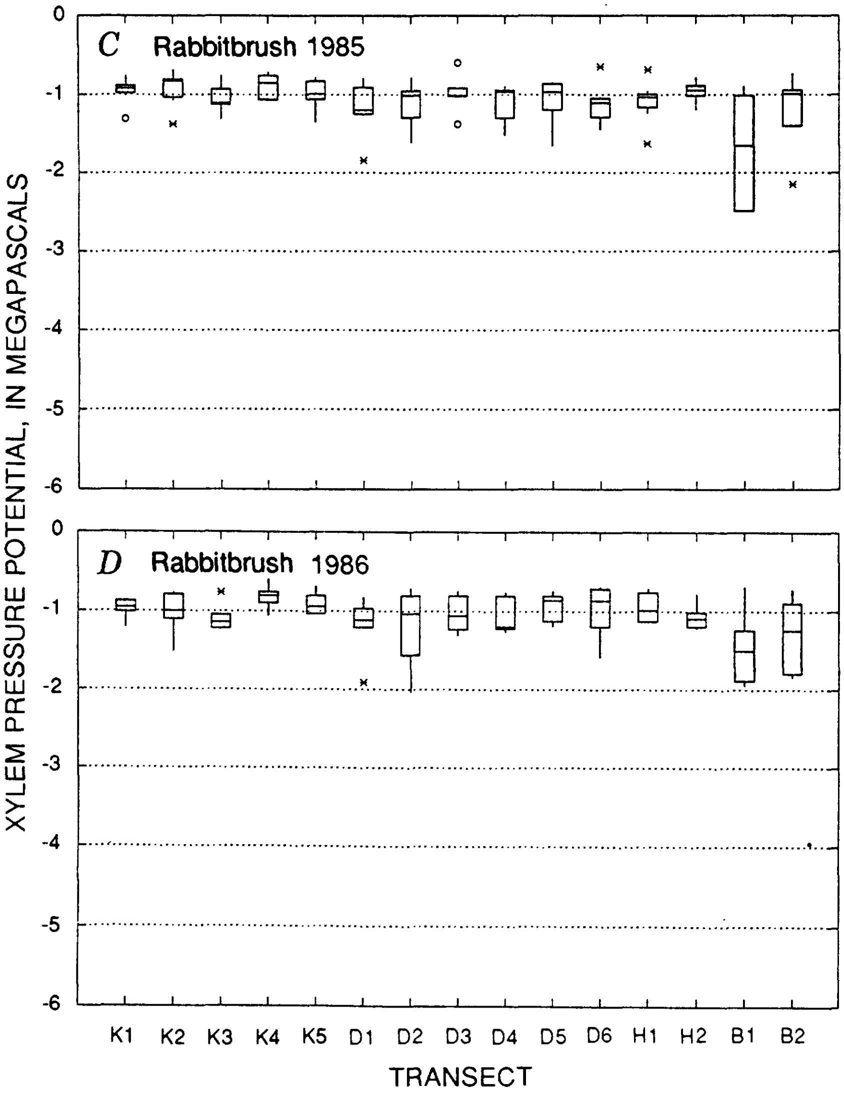


Figure 22. Continued.

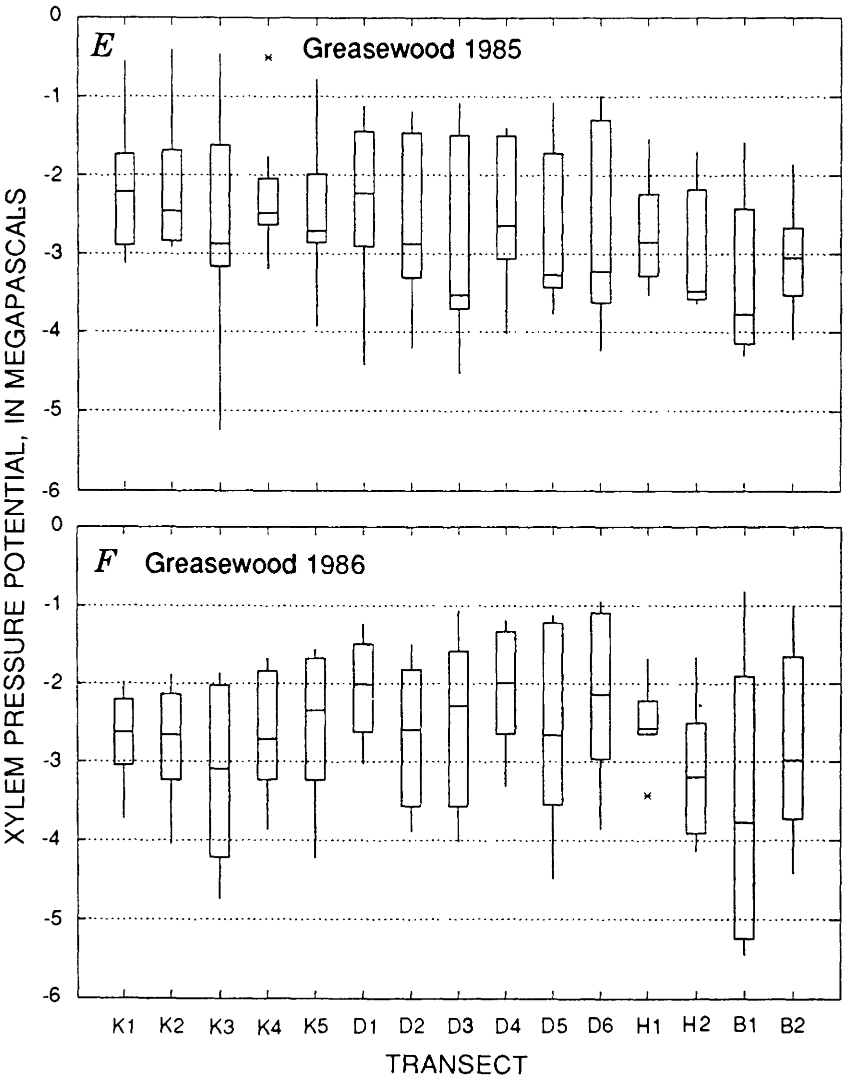


Figure 22. Continued.

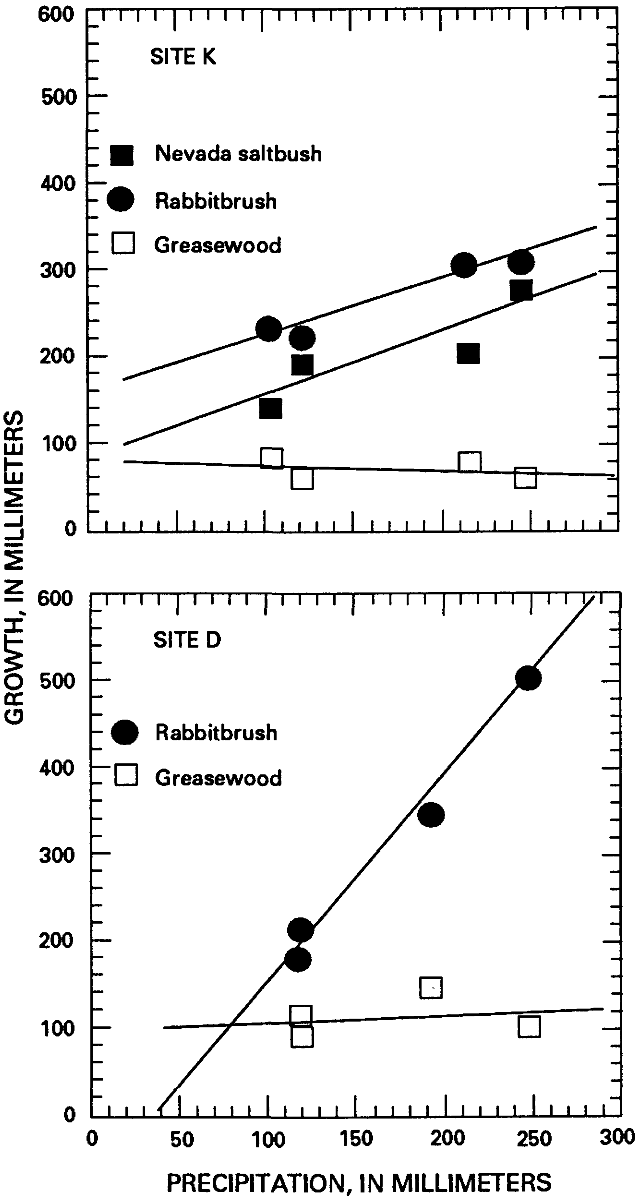


Figure 23. Plant growth in relation to precipitation at sites K and D, 1983–86. Lines represent least-squares regression.

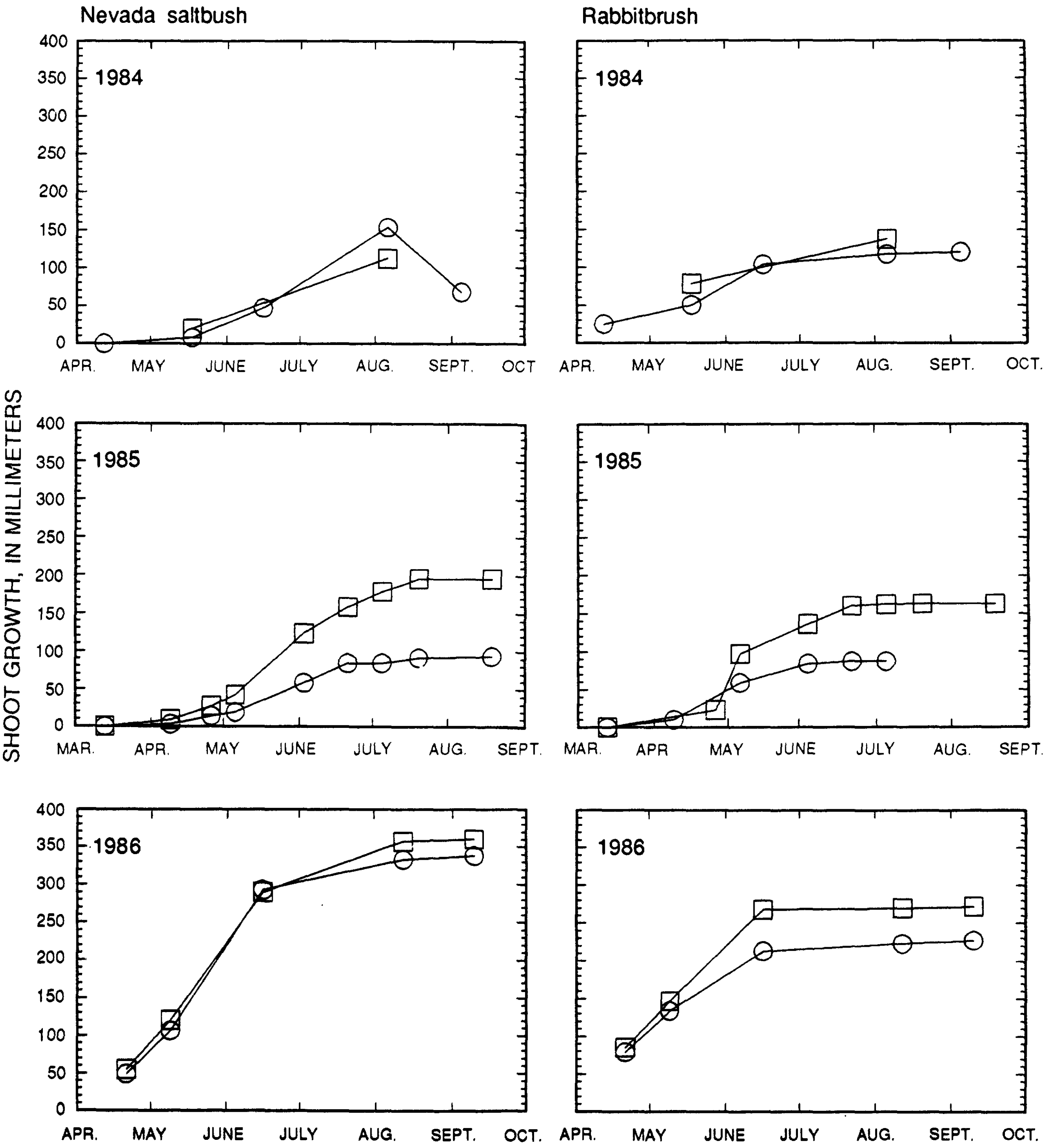


Figure 24. Growth of Nevada saltbush, rabbitbrush, and greasewood at transects B1 (circles) and B2 (squares) in 1984, 1985, and 1986.

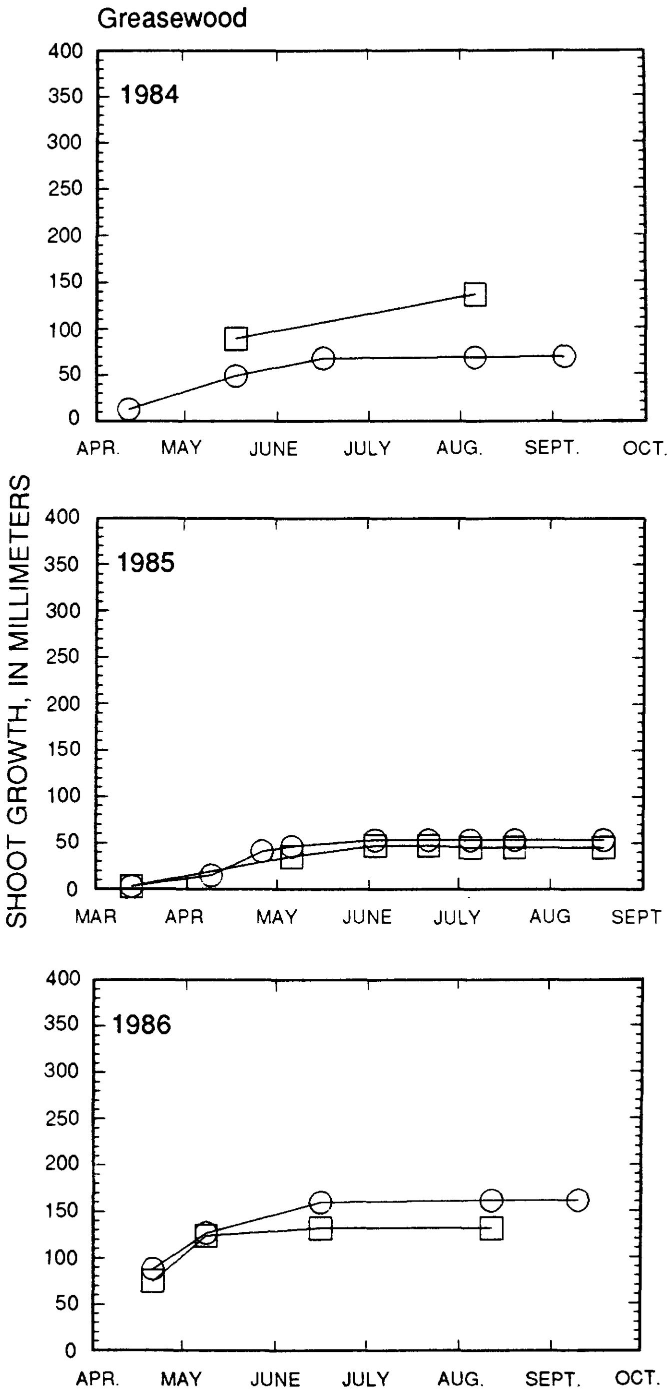


Figure 24. Continued.

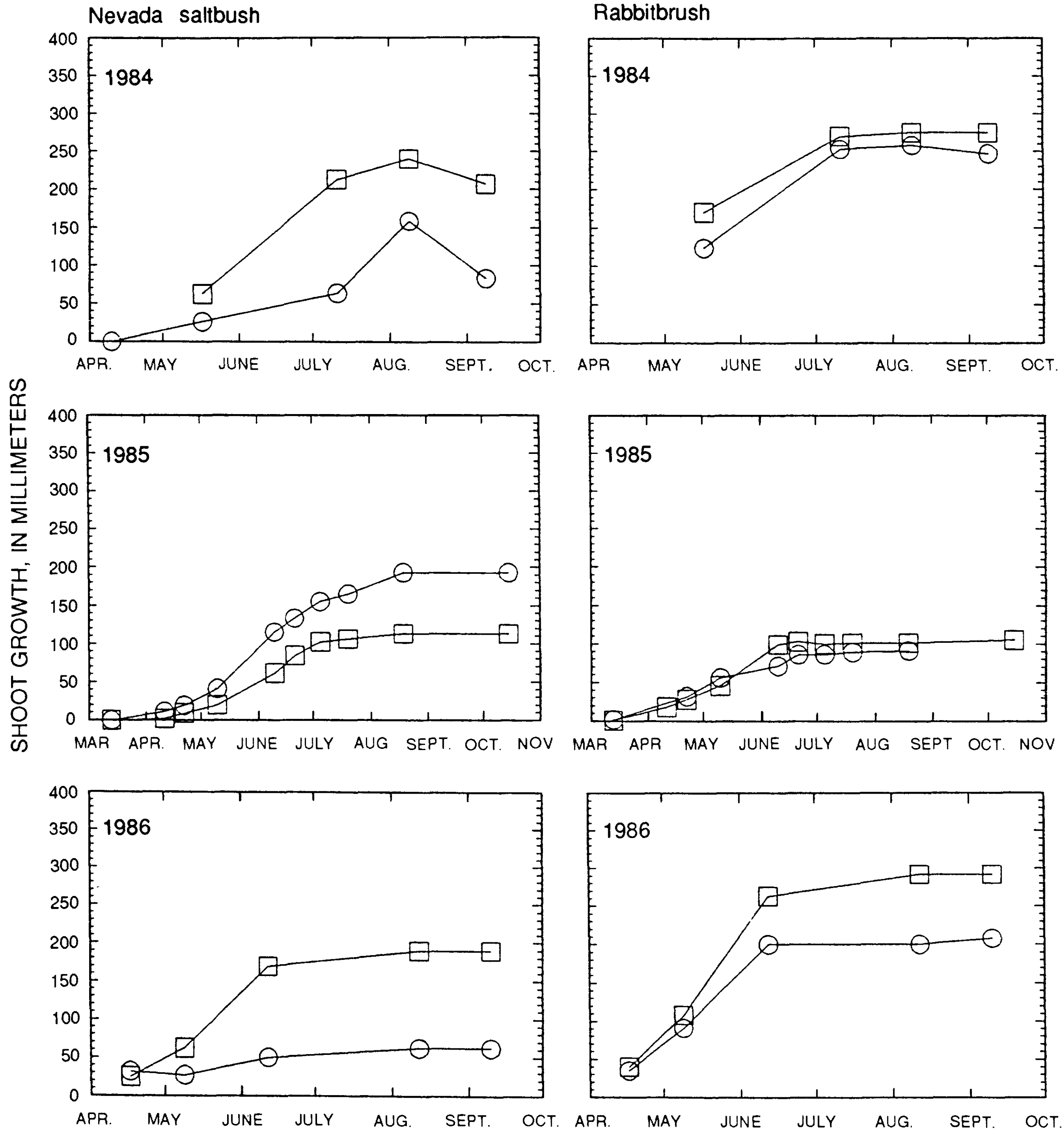


Figure 25. Growth of Nevada saltbush, rabbitbrush, and greasewood at transects H1 (circles) and H2 (squares) in 1984, 1985, and 1986.

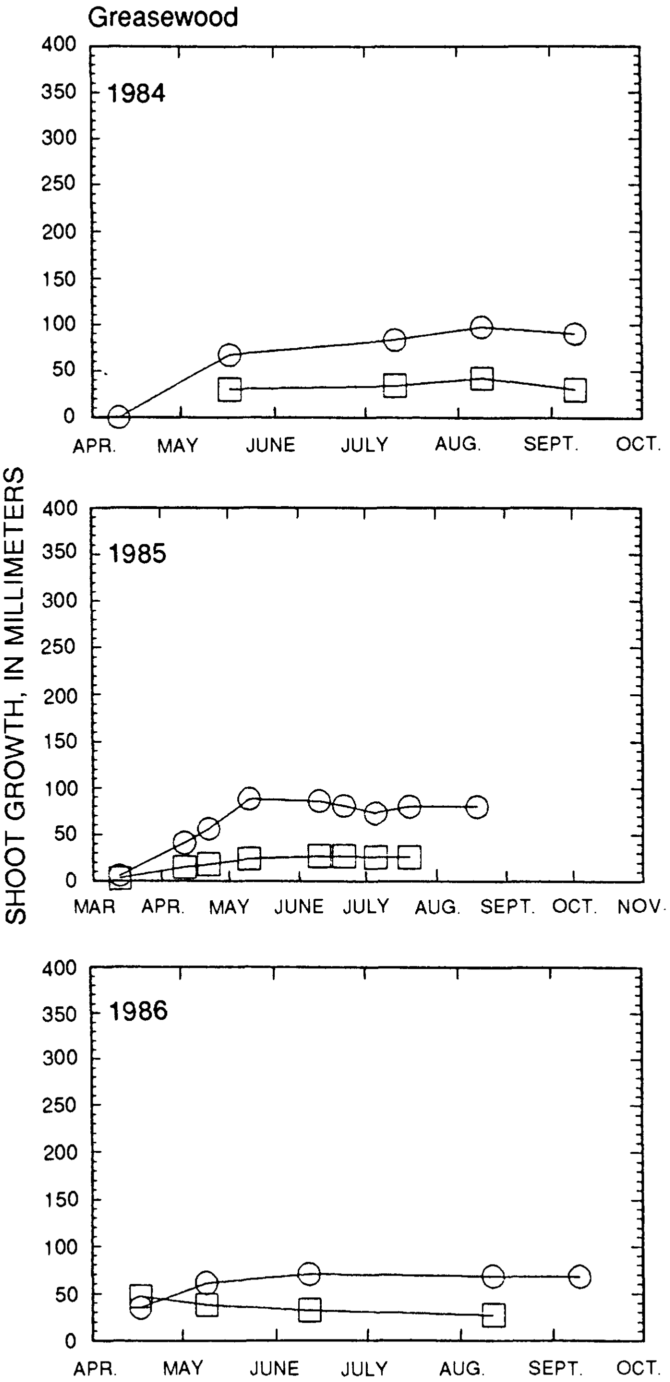


Figure 25. Continued.

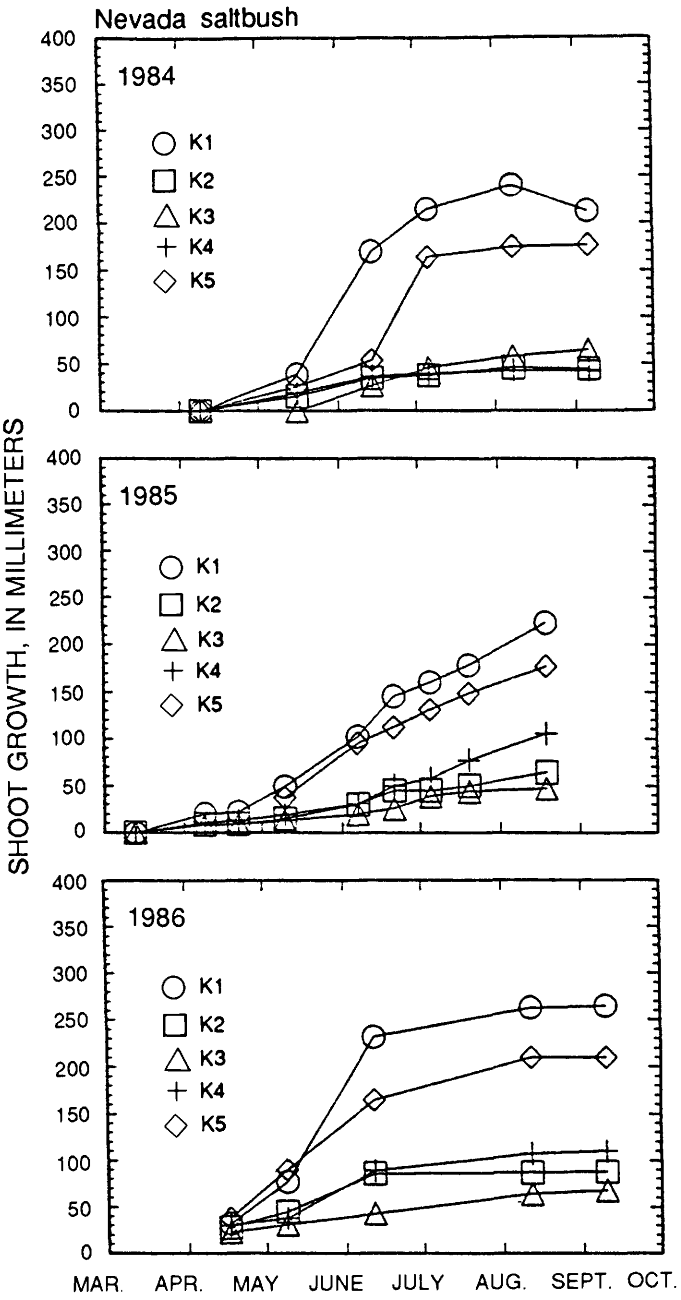


Figure 26. Growth of Nevada saltbush at transects K1–K5, 1984–86.

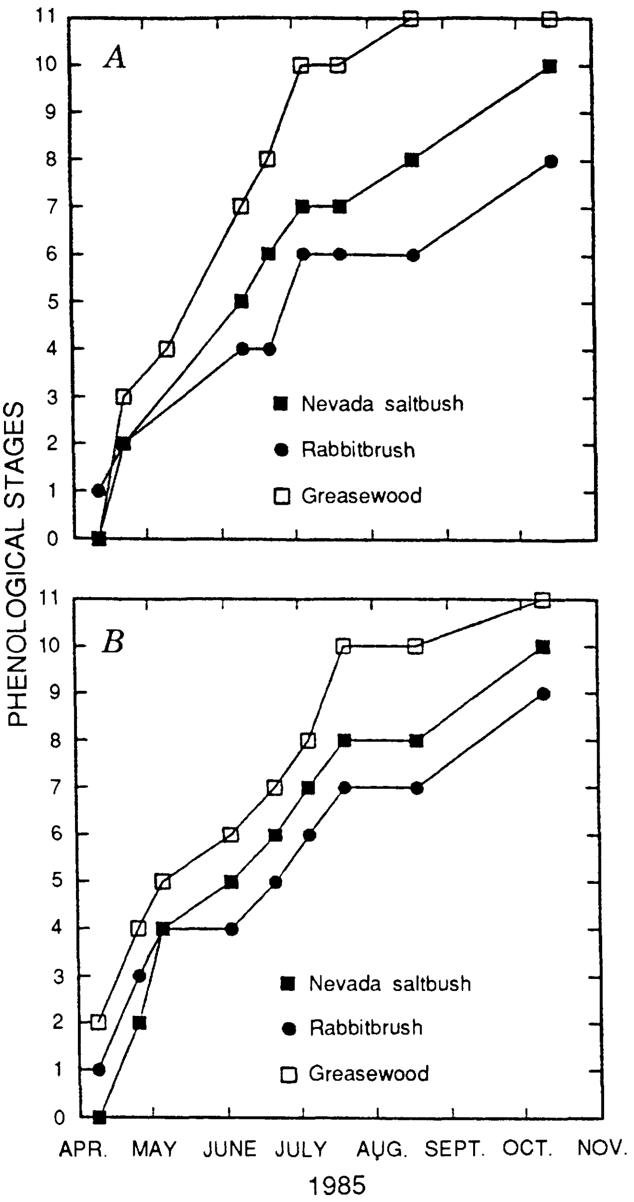


Figure 27. Comparative growth stages of Nevada saltbush, rabbitbrush, and greasewood at all vegetation transects, 1985. *A*, Sites B and D. *B*, Sites H and K.

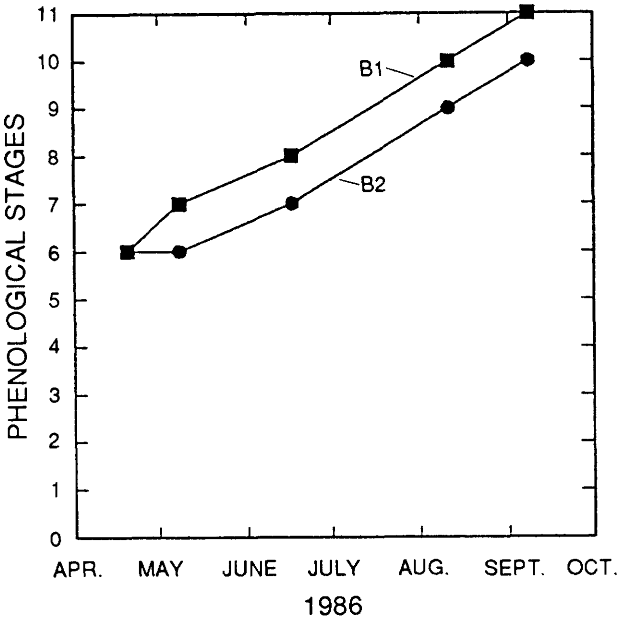


Figure 28. Growth stages of greasewood at vegetation transects B1 and B2, 1986.