THE ECONOMIC VALUE OF WATER FOR RANGE FORAGE PRODUCTION

BY

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ABSTRACT

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Dr. L. Allen Torell, Chair

This thesis had multiple objectives including building a database with user's manual that summarizes weather data collected on the NMSU's Corona Range and Livestock Research Center; describing weather conditions on the Corona Ranch over the period, July 17, 1990 to April 18, 2006; estimating the relationship between rainfall occurrence and soil moisture on the Corona Ranch; examining the degree to which soil moisture and rainfall can be used to predict annual forage production; and estimating the forage response and economic value of forage resulting from rainfall events of different magnitudes and with different timing within the year.

A database summarizing Corona Ranch weather data collected over 16 years was built in MS ACCESS^{TM}. Weather-related data collected on the ranch were then used to develop regression equations and quantify the relationship between rainfall, soil moisture, and annual grass biomass production. Three different regression equations were developed for estimating the relationship between grass production and weather related conditions. Overstory-understory relationships for broom snakeweed (*Gutierrezia sarothrae* [Pursh] Britt. and Rusby) were also considered in the equations.

The estimated regression equations were used to estimate how forage production would change during selected years with additional rainstorms of different magnitudes. Forage response and economic value of a storm was found to depend on soil moisture conditions at the time of the storm, the timing of the rainfall event, and the seasonality of grass growth. During 2003, a severe drought year on the Corona Ranch, an additional April storm dropping 25.4 mm (1 in) of moisture was estimated to increase grass biomass by 84 kg/ha which is a 30% increase in the amount of production for the year. This one storm would add a minimum of $13,500 to the total ranch in added production on blue grama (*Bouteloua gracilis*) grassland areas.

The number of days with favorable moisture and temperature over the March through October growing season was found to have a significant influence on grass yield as would be expected. The presence of snakeweed had a significant negative effect on the marginal increase of grass yield resulting from rainfall which highlights the importance of controlling broom snakeweed and other woody plants if the full benefit of rainfall events on rangeland is to be realized.

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INTRODUCTION

Overview

Water is perhaps the most important factor for forage production on western rangelands. Precipitation levels in the Western states are relatively low and this results in periodic shortages of soil moisture. This water shortage highly affects the growth of rangeland forage. Moreover, rangelands lose water in many different ways including transpiration by unwanted vegetation, over-the-surface water run-off, deep percolation, and evaporation.

It is widely recognized that rainfall and ultimately soil moisture are the most limiting factors in range forage production. Reynolds (1954) found that annual precipitation was almost entirely responsible for fluctuations in forage yield on dry southwestern grasslands, and this wide variability in annual forage yield is a major production risk for ranchers. Coupled with periodic water shortage, if a ranch is also infested with undesirable brush species, annual forage production can be further suppressed.

McDaniel et al. (1993) found heavy infestations of broom snakeweed (*Gutierrezia sarothrae* [Pursh] Britt. and Rusby) suppressed herbaceous production during average and above average rainfall years to levels that are comparable to those realized during severe drought. The dual effect of low precipitation and snakeweed infestation suppressed forage production to below 200 kg/ha at two sites in southeastern New Mexico. Other brush and forest overstory species have been shown to similarly suppress understory grass production (Bartlett and Betters 1983).

According to Keller (1971) more soil moisture is lost to unproductive overstory woody plants on arid range than is transpired by the forage itself. He further noted that unwanted vegetation consumed all the water available and desirable forages had been forced out on possibly a hundred million rangeland acres. The approximate annual amount of water lost due to undesired vegetation from a representative hectare of western range is between 31 mm and 63 mm (Keller 1971).

With periodic drought and competition with overstory woody species, maintaining an adequate forage supply is problematic. It is a major expense to reduce herd size and to buy alternative feeds. Further, failing to reduce livestock numbers during drought and overgrazing the range can have long-term negative impacts to future rangeland productivity and can also reduce livestock body condition and productivity.

Incorporating precipitation-sensitive grazing strategies and range improvement programs is an ongoing problem for rangeland managers. Improving these decisions starts with a basic understanding of rainfall patterns, drought frequency, and how rainfall events are related to forage and animal production. This thesis will provide estimates for some of these key relationships for the New Mexico State University's Corona Range and Livestock Research Center (CRLRC) which is located about 13 km (8 miles) east of Corona, New Mexico. Hourly weather data including air temperature, soil temperature, relative humidity, wind speed, wind direction, and rainfall have been collected at two study sites on the CRLRC since 1991. Soil moisture at 10 cm and average soil moisture between 10 cm and 30 cm depth have been measured at the weather stations since 2001, but with periodic lapses in data recordings. Forage production and the amount of broom snakeweed canopy were recorded each fall for various chemical and burning research plots initiated for broom snakeweed control in 1990. The brush control treatments coupled with natural die-off of snakeweed provided a wide range of snakeweed canopies from which to estimate overstory-understory relationships.

Study Objectives

The primary objective of this research is to estimate how annual forage production on blue grama (*Bouteloua gracilis*) dominated rangelands is related to rainfall and other environmental and weather factors, and the amount of broom snakeweed present. The economic value of rainfall events of different magnitude will be computed by estimating how soil moisture is accumulated in the soil and how forage production relates to soil moisture and overstory brush canopy. Because range forage production is dependent on periodic and scattered rainfall events, and moisture cannot be reallocated to other uses as it percolates into the soil surface, knowing the economic value of water for forage production will not be useful in the continuing debate about how water should be allocated among competing uses. It may be useful to know the economic value of water for rangeland production for cloud seeding or other strategies that could be used to increase rainfall amounts and range forage production. Estimating the economic value of adding more water on rangeland, or improving weather forecasts for livestock producers, also starts with an understanding of how rainfall events relate to the production of forage species.

In this thesis the relative economic value of water for forage production versus other uses will be estimated, and more importantly stocking rate and range management decisions will be improved by better understanding the expected variability and frequency of rainfall events that result in sustainable range forage production.

Specific objectives of this research include the following:

1. Build a database with user's manual that summarizes weather data collected over 16 years on the NMSU's Corona Range and Livestock Research Center. This database and detail about the database structure and update procedure will provide continued access to key Corona Ranch weather data for NMSU researchers.
2. Describe weather conditions and the variability of key weather related variables including temperature and rainfall on the Corona Ranch over the weather and forage yield data collection period, July 17, 1990 to April 18, 2006.
3. Estimate the relationship between rainfall occurrence and soil moisture on the Corona Ranch. Quantifying this relationship will allow estimation of soil moisture during years prior to 2001 when

forage production data were gathered but soil moisture measurements were not collected.

4. Various authors have estimated how forage production is related to rainfall amounts, but these quantification attempts have been relatively unsuccessful. It is also recognized that ultimately the amount of available soil moisture and interactions with other environmental factors determines herbaceous production over the growing season. The degree to which forage predictive equations can be improved by using soil moisture measurements instead of rainfall will be explored.

5. Estimate the forage response and economic value of forage resulting from rainfall events of different magnitudes and with different timing within the year.

LITERATURE REVIEW

Predicting Forage Production from Rainfall

Sneva and Hyder (1962) used indices of precipitation and herbage yield measured at range sites in Oregon, Utah, and Idaho to derive a single herbage-response equation. Grass species considered included crested wheatgrass (*Agropyron sp.*) and native grass species common on sagebrush-bunchgrass rangeland at the Squaw Butte Research Range near Burns, Oregon. Native rangeland sites at research areas near Dubois, Idaho and Milford, Utah were also considered. Thirteen different data series were considered for different grass species, years, and locations. Sneva and Hyder (1962) found that precipitation frequency distributions of semiarid and arid regions usually show a skewness to the right, and thus the median precipitation amount better estimated the long-term forage yield expectation. They estimated median herbage yield equations for each data series based on median rainfall amounts. A single regression line was estimated from the indices to represent a common yield dependence on rainfall ($\hat{Y}$ =1.11X-10.6, r^2=0.77). The pooled linear equation suggests that a 1 unit increase in the precipitation index will cause a 1.11 unit increase in the herbage yield index.

Recently, Khumalo and Holechek (2005) used a similar procedure to evaluate the relationship between perennial grass production and precipitation characteristics using data collected over a 34-year period (1969-2002) at the Chihuahuan Desert Rangeland Research Center (CDRRC) near Las Cruces, New Mexico. They estimated variation in the production of perennial grasses was very high in the Chihuahuan Desert with the highest coefficient of variation of all long-term forage production datasets compared in their study. Total precipitation from December through September showed the highest correlation (r = 0.82) with grass production. A quadratic model using only December through September precipitation produced the best forage yield predictions ($\hat{Y}$ = 4.04 - 0.24X + 0.012X^2, R^2=0.72). The implied marginal value of water for forage production was increasing throughout the relevant range.

Dahl (1963), working on a Sandhills range site at the Eastern Colorado Range Station located 16 miles north of Akron, Colorado, found that precipitation in the preceding two years and yield of grass in the current year were significantly correlated, but the relationship could be improved by considering, in addition, the quantity of soil moisture or the depth of moisture distribution. He found that if a single factor was used to predict forage yield, soil moisture or depth of moist soil would be best. Results and management recommendations were similar to those of Cole and Mathews (1940) and Rogler and Haas (1947) that suggested using depth of wet soil as an approximation of water content in the soil, because of its practical measurement. Available soil moisture was considered to be a better predictor of forage yield, however. Dahl (1963) estimated the linear relation between fall grass yield (lb/acre) measured on August 7 and depth of soil moisture (inches) on April 15 to be $\hat{Y}$ =859+7.67X (r^2=0.63). Herbage yield was not correlated with rainfall during the spring (May-June), but it was significantly correlated with summer and fall rainfall.

One of the earliest studies about forage production and precipitation relationships in the southwestern United States, where warm season grasses predominate, was done by Pieper et al. (1971) on loamy, shallow, and hill sites at the Fort Stanton Cooperative Range Research Station in south-central New Mexico. Blue grama (*Bouteloua gracilis*) was the dominate grass species on all research plots. For loamy locations, July and August precipitation (added together) accounted for 25 percent of the variation in total annual herbage production. For every inch of additional July-August rainfall 33 pounds/acre (37 kg/ha) of forage were added ($\hat{Y}$ =745.2+33.2X, r^2=0.25). Total herbage production was significantly dependent on the growing season (June to September) precipitation for loamy alluvial locations. For every inch of additional June-September precipitation, about 144 pounds of herbage per acre (161.4 kg/ha) were produced ($\hat{Y}$ =-226.9+144.1X, r^2=0.71). Each inch of July and August precipitation added about 56 pounds/acre (62.8 kg/ha) of forage ($\hat{Y}$ = -263.5+55.7X, r^2=0.42).

Nelson (1934) studied on the Jornada Experimental Range near Las Cruces, NM and found that current summer rainfall was highly correlated with the average height and growth of black grama (*Bouteloua eripoda*). Similarly, McDaniel et al. (1993), studying overstory-understory relationships for broom snakeweed and blue grama grass near Vaughn and Roswell, New Mexico, estimated that each cm of April through June rainfall added about 20 kg/ha (18 pounds/acre) to grass yield. Precipitation during July through September added 16 kg/ha (14 pounds/acre) at the Vaughn, New Mexico study site and 11 kg/ha (10 pounds/acre) at the Roswell site. Fall and winter rainfall did not contribute a significant amount to annual forage production.

Cable (1975) worked on the Santa Rita Experimental Range in southern Arizona with precipitation and grass production data collected over a 10-year period on four pastures. The study pastures were predominated by native perennial grasses including tall Threeawns (primarily *Aristida hamulosa* Henr. and *A. ternipes* Cav.), Arizona cottontop, slender grama (*Bouteloua filiformis* [Fourn.] Griffiths), black grama, and sideoats grama (*B. curtipendula* [Michx.] Torr.). Two of the pastures had an overstory of an invasive stand of velvet mesquite (*Prosopis velutina*). It was found that perennial grass production (with or without overstory) was primarily dependent on current and previous summer rainfall. The best estimated multiple regression equation for predicting forage yield included current August rainfall, previous June through September rainfall, and the interaction product of these two. However, the interaction product alone explained nearly as much of the variability in year-to-year grass production as did the multiple regression. Winter and spring moisture proved to have little influence on current year grass production, whereas the previous summer's precipitation had a strong influence.

Rogler and Haas (1947) studied the relationship between the amount of fall soil moisture and the following year range production using eighteen years of data collected at the Northern Great Plains Field Station, Mandan, N.D. They obtained highly significant coefficients of 0.72 and 0.74 for the correlation between forage yield and available soil moisture in the surface 3 feet (91 cm) and 6 feet (183 cm), respectively. For a one inch increase in soil moisture in the surface 3 feet (91 cm), forage production increased by 183 pounds per acre (205 kg/ha). Forage production increased by 111 pounds per acre (124 kg/ha) for each additional unit of soil moisture in the surface 6 feet (183 cm). Soil was only considered moist when 0.5 inch (13 mm) or more moisture was present in a foot section of soil. When the soil was dry, 88% of the forage yields were below the mean level of 372 pounds per acre (417 kg/ha).

Bork et al. (2001) studied the relationship between grassland herbage production and precipitation within the Boreal region of central Alberta in Canada. Each mm of current year precipitation added about 10 kg/ha (8.9 pounds/acre) of herbage production ($\hat{Y}$ =-131+10.2X, R^2=0.58). However, water year (previous May-August) precipitation had much lower correlations with herbage production on upland grasslands. Lowland herbage production showed a strong negative curvilinear relationship with precipitation ($\hat{Y}$ =-46199+144X-0.098X^2, R^2=0.65). According to Bork et al. (2001) the factors affecting lowland herbage production were soil temperature and the timing of precipitation.

Overstory/Understory Relationships for Broom Snakeweed

Ueckert (1979) evaluated competition between broom snakeweed and perennial grasses and the effect of broom snakeweed on soil water depletion on the rangeland portion of the Texas Tech University Farm in Lubbock County. Analysis of variance was used to examine the data on cover repetition, standing crop biomass, and soil water. This study showed that perennial shortgrasses did not respond immediately to removal of a dense snakeweed stand (387 plants/m^2) even though considerable precipitation was received. However, one year following complete removal of snakeweed, production of perennial grasses increased by 107% (1,175 kg/ha) and after two years, by 324% (2,201 kg/ha) compared to undisturbed snakeweed areas. During the two year study period, reducing snakeweed density by 25% or 50% had little effect on forage production. Reducing snakeweed density by 25% increased grass production by only 15%.

Ueckert (1979) found that juvenile broom snakeweed plants were using water from the upper 15 to 45 cm of the soil profile. After perennial grasses regained vigor, following complete removal of broom snakeweed, soil water depletion increased. Each centimeter of precipitation added 23.7 kg of perennial grass herbage on snakeweed infested plots as compared to 49.2 kg/cm on snakeweed free plots for the 1976 study. In 1977, 10.6 kg of herbage was produced per cm of precipitation on snakeweed-invaded rangeland, compared to 45.2 kg/cm on snakeweed free rangeland. Precipitation-use efficiency for forage production was from 2.1 to 4.3 times greater on snakeweed-free rangeland as compared to snakeweed-infested rangeland.

McDaniel et al. (1993) defined equations expressing overstory-understory relationships for broom snakeweed growing on blue grama dominated grasslands in central New Mexico. They provided model estimation from broom snakeweed and grass biomass data collected over an eleven year period at two permanent study sites near Vaughn and Roswell, New Mexico. A 5-parameter sigmoidal growth curve and an exponential equation were estimated. The sigmoid and exponential equations explained the relationship between snakeweed and grass biomass equally well. Estimated curves showed diminishing marginal suppression of grass yield as snakeweed biomass increased, similar to the findings of Ueckert (1979). Average grass production across years and sites was 667 kg/ha without broom snakeweed, and 212 kg/ha with an average snakeweed biomass of 600 kg/ha. Little, if any, forage was produced when snakeweed production was above 600 kg/ha regardless the amount of rainfall (McDaniel et al. 1993). Although parameter estimates were slightly different between sites, snakeweed and grass biomass were found to be inversely related.

Carpenter et al. (1991) conducted a study to analyze the economics of snakeweed control on the Southern Plain of Texas. Part of the study also involved determining overstory-understory relationships for broom snakeweed. They used multiple regression models to explain variability in annual grass production. Annual snakeweed production, soil type, and interaction terms between precipitation and soil type were used to explain the variability in annual grass production. Results of this study were consistent with the findings of McDaniel et al. (1993) in that summer rainfall was found to be an important determinant of herbage production. Winter rainfall was not found to have a significant influence on production of warm season grasses.

Relating Rainfall to Soil Moisture

The quantity of water in soil is usually expressed in two different units, as volumetric water content or gravimetric water content. Volumetric water content is the volume of liquid water per volume of soil. The gravimetric water content is the mass of water per mass of dry soil (Jury et al. 1991).

According to the theories of water movement in soil, when two points of different water potentials come into contact with each other, water flows from high to low potential and tends to restore equilibrium. When all soil pores are filled it is called the maximum retentive capacity or saturation. A portion of soil water, the gravitational water, readily percolates downward, primarily under the influence of gravity (hydraulic gradient). Once the gravitational water drains away, the system is left with its maximum capillary water. This is the maximum amount of water useful to plants and is called field capacity. At field capacity a soil is nearly at its lowest plastic limit (where soil will not behave as a liquid). The point at which water requirements are unmet so that plants remain wilted all day is called the permanent wilting point. Water with potential below the wilting point is unavailable to plants.

On non-irrigated rangelands, the net addition of water to the soil profile over a period of time can be represented by the amount of precipitation less surface runoff. Infiltration causes the soil to become wetter with time. Water at the leading edge of the wetting soil pattern gradually advances into the drier soil region ahead of the front. All theoretical models of vertical infiltration share the common feature that the infiltration rate is higher when water first enters the soil and decreases with time as the wetting front moves away from the surface.

In general, wetting or drying of the soil occurs as water flows. In steady state, water can flow upward or downward in the soil. Water flows upwards when evaporation is occurring. Water evaporation in the field is not a steady-state process, but a nearly steady upward flow from a water table to a bare soil surface may be established if the daily evaporative demand is reasonably consistent for a long period of time. The rate of evaporation depends on the type of soil. When the distance between the water table and the surface is great enough, coarse textured soils, containing mostly large pores, offer more resistance to upward water flow than do the finer textured soils with a broader distribution of pore sizes. The rate of evaporation from a wet, bare soil surface is limited by external meteorological conditions such as wind speed, relative humidity, and the flux of radiant energy to the surface. In contrast, water loss from a soil with a dry surface layer is regulated primarily by soil water resistances that limit the rate at which water moves upward to the evaporating surface.

Evaporation losses from initially wetted soil as a function of time were modeled by Ritchie (1972) using a two-stage evaporation model. During the first stage the soil surface is wet and the upward flow of water is high enough to evaporate. This lasts for a period of time after rainfall ceases. Gradually, gravity driven drainage and water loss by evaporation depletes the surface layer, and it dries to a point where regulation of subsequent loss of water shifts to the soil. This sets off the onset of the second stage of drying. In the second stage of evaporation the soil water flow theory predicts that if gravity is neglected, cumulative loss of water is proportional to the square root of time (Jury et al. 1991, p. 154).

The gravimetric water content of a moist soil sample is measured by weighing the sample, drying it to remove the water, and then reweighing it (Jury et al. 1991). The conventional procedure of drying is to place the sample of moist soil in an oven at 105^{o}C for 24 hours. This process removes the interparticle water but not the water molecules trapped between clay layers. The volumetric water content can be computed by multiplying the gravimetric water content by the dry soil bulk density and then dividing the product by the density of water. Soil bulk density is defined as the mass (weight) of a unit volume of dry soil (Brady and Weil 1996). The dry soil bulk density can be measured by estimating the volume of an undisturbed sample of soil. However, it is extremely difficult to take such a sample without compacting the soil and thus changing its density.

Gamma ray attenuation can be used to measure the volumetric water content in a nondestructive way (Jury et al. 1991). In this method a narrow beam of gamma radiation is transmitted through a soil sample of known thickness and is collected on its exit with the help of a detector. The detector records only the gamma rays that do not scatter off of an atom while passing through the soil. The gamma ray has a characteristic of interacting with any obstacle in its path depending on the type and density of the substance. Changes in the reading of transmitted gamma radiation at different times are attributed to a change in soil moisture. To directly measure volumetric soil moisture in the field the neutron attenuation method is used exclusively. In this method a radiation source emits high-energy neutrons which collide with the nuclei of atoms in the surrounding soil. The neutrons are slowed substantially and reach the characteristics of thermal motion of the hydrogen atoms in the soil when they collide with hydrogen nuclei. The thermalized neutron counts are proportional to the density of hydrogen atoms surrounding the source. A calibration curve is obtained, showing the number of counts over time versus the amount of hydrogen present in the form of liquid water. The calibration curve can be converted to a relationship between volumetric water content and thermal neutron count rate with simultaneous measurements of water content by soil coring.

A recent method to indirectly estimate volumetric water content is time domain reflectometry (TDR). With this method the permittivity or dielectric constant of the soil and the subsequent calibration of this property with the volumetric water content is measured. Permittivity relates to a material’s ability to transmit (or permit) an electric field. The permittivity of a material is usually given relative to that of a vacuum, as a relative permittivity, also called the dielectric constant. The dielectric constant of soil is measured by placing a prong with two parallel waveguides into the soil and sending a step pulse of electromagnetic radiation along the guides. When that pulse reaches the end of the prong, part or all of the pulse energy is reflected back to the source. The travel time and velocity of the pulse can be measured by an oscilloscope. The permittivity of soil can be estimated from the travel time, and the volumetric water content of soil is calculated from permittivity (Kelleners et al. 2005).

MATERIALS AND METHODS

Study Sites

This research was conducted at the New Mexico State University's Corona Range and Livestock Research Center (CRLRC). Two long-term snakeweed study sites referred to as 'South House' and 'Oil Well', each within 8 ha enclosures and located about 10 km from one another were established on the Corona Ranch in mid-1990 by Dr. Kirk. C. McDaniel (Department of Animal and Range Science, New Mexico State University). This study was conducted using weather data, grass yield data, and snakeweed production data collected at the South House and Oil Well research sites over the 1990-2005 period.

The Corona Ranch is a working ranch laboratory, located in Lincoln and Torrance counties, New Mexico approximately 306 km northeast of Las Cruces and 13 km east of the village of Corona. The ranch covers approximately 11,396 ha (28,160 acres) in the north central part of Lincoln county and the southeast corner of Torrance county. Historically this area has been used for sheep and cattle production, though the 8 ha enclosures of the two snakeweed study sites have not been grazed since they were established in 1990. The ranch is characterized by a semiarid, continental climate with wide ranges in diurnal and seasonal temperatures, variable but relatively low precipitation, and plentiful sunshine. More detail about the weather conditions realized on the Corona Ranch over the September 1989 through March 2006 study period is given in the results section of this thesis.

The Corona Ranch lies within the Great Plains province. The general topography of the ranch includes gently rolling to flat plains, limestone sinkholes characteristic of Karst topography, sand dunes, and steep rocky outcrops and mesas. Hart (1992), Berry (1992), and Ebel (2006) provide detailed descriptions of the vegetation and soils found at the two study sites. As noted in these earlier dissertation and thesis reports, elevation is 1875 m (6150 ft) at the South House site and 1860 m (6100 ft) at the Oil Well site. The soil on both study sites are of the Taipa-Dean loam association, which are shallow and underlain by a highly calcareous limestone bedrock. The Taipa loam is a fine-loamy, mixed, mesic, Ustollic Haplagrid, and Dean loam is a fine carbonatic, mesic Ustollic Calcioathid. Berry (1992) reported the average soil particle sizes for the south house pasture plots, measured at 10-20 cm, were 50% sand, 41% silt, and 9% clay.

The Corona Ranch has two major types of vegetation, blue grama grassland and pinyon-juniper woodland (Hart 1992). The two research sites are located in the blue grama grassland area. Broom snakeweed stands are also visible periodically at the two study sites. Other common plants at the study sites are winterfat (*Ceratoides lanata* [Pursh.] J.T. Howell), cholla (*Opunita imbricata* [Haw.] DC.), wolftail (*Lycurus phleoides* [H.B.K.], sand dropseed (*Sporobofus cryptundrus* [Torr.] A. Gray), squirreltail (*Elymus longifolius* [Smith] Gould), and threeawns (*Aristida* spp.).

Weather Data

Hourly weather conditions were monitored at each study site starting at 12 P.M. on July 17, 1990 at South House and at 1 A.M. on November 9, 1990 at Oil Well using automated weather stations (Campbell Scientific model CR-10 multiport data loggers). The data loggers were powered by 9-V batteries during the early years which proved to be problematic. The power source was eventually switched to a solar recharged battery system. These weather stations recorded hourly air temperature, soil temperature (at 10 and 50 cm from the surface), relative humidity, wind speed, wind direction, and rainfall. The South House data logger recorded 116,517 apparently valid hourly measurements from July 17, 1990 to April 18, 2006. This was 85% of the hours that elapsed over the period. Similarly, the Oil Well recorder had 117,439 recordings for 86% of the elapsed hours.

To relate weather factors to herbaceous forage production during 1990 required weather data for the entire year. This earlier weather data was filled in from nearby NOAA weather stations with the recorded data series starting on September 24, 1989. This start date was chosen because there was a substantial rainfall event on September 25, 1989 that would have saturated the soils to provide a saturated starting point for predicting changes in soil moisture, as discussed later.

Monitoring of soil moisture started in September and October of 2001 at the South House and Oil Well study sites, respectively. Soil volumetric water content at a 10-cm depth and average soil moisture between 10 and 30 cm depth were recorded using TDR soil moisture probes (CS 615-L, Campbell Scientific Inc., Logan, UT).

Measurements of soil permittivity are converted to estimates of volumetric soil water content using a quadratic equation within the data logger software. According to the instruction manual for the CS615-L probe, estimates of volumetric water content are accurate within $\pm 2.0\%$ using standard calibration (Campbell Scientific Inc. 1996, p. 2). For the soil characteristics found at the study sites a recorded soil moisture mearurement of about 0.5 implies soil saturation whereas a value near 0.1 implies the soil is extremely dry.

All the weather data were downloaded and recorded into separate spreadsheet files over the 16-year study period. The weather data were later combined into an MS Access^{TM} database for presentation and comparison across years. Detail about the database's structure, use, and data updating procedures are given in Appendix A.

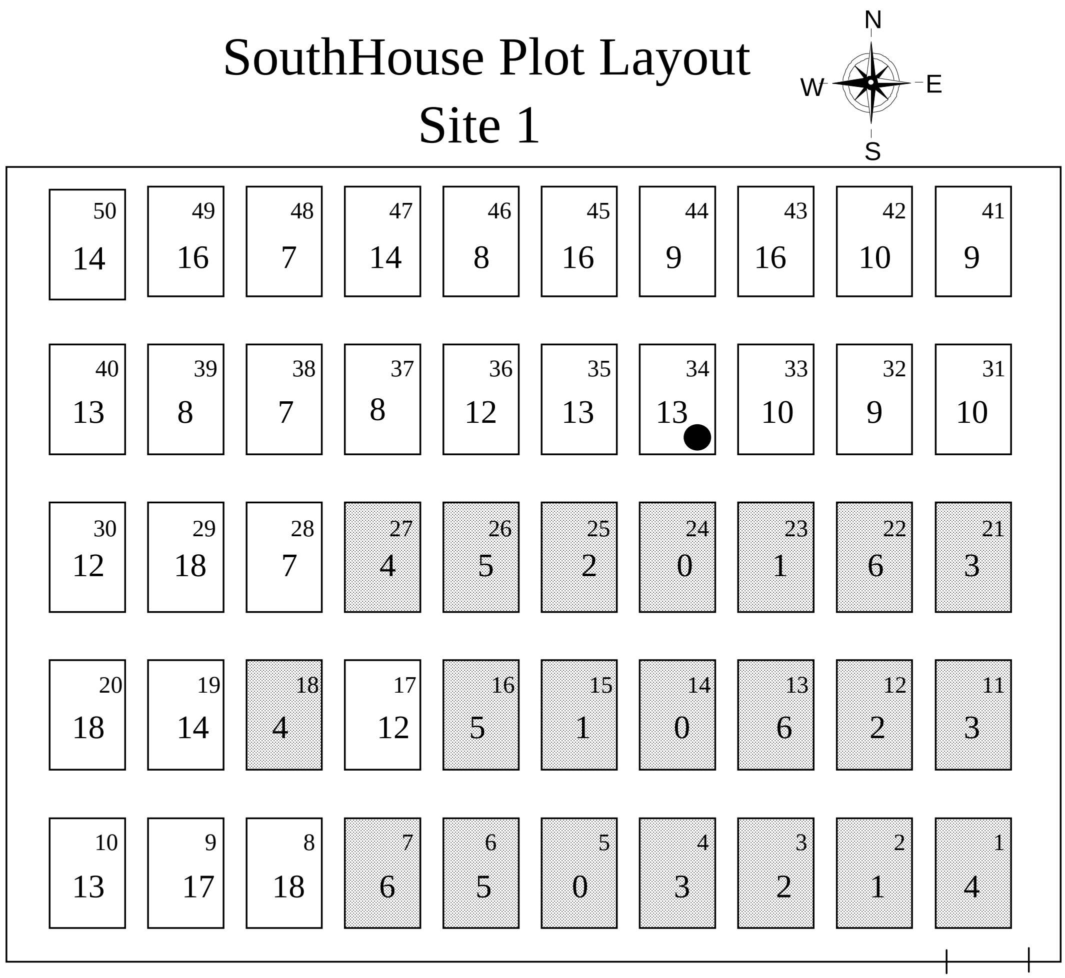
The weather-recording devices used in this study, like all other weather recording devices, had periodic problems resulting in missing values for weather variables. Appendix A includes additional detail about how missing weather data were handled, but briefly, data were first substituted between the two study sites when the other recorder was functioning, then from the weather station located at the North Camp facility on the Corona Ranch, and then from nearby NOAA (National Oceanic and Atmospheric Administration) weather stations including Ramon and Corona 10 SW. The North Camp weather station was initiated in 1993.

Grass Yield and Snakeweed Production Data

Snakeweed control treatments implemented in 1990 by Hart (1992) and Carroll (1994) were examined to evaluate vegetation response to varying levels of snakeweed infestation and to different weather conditions. A completely randomized design with treatments replicated three times on 20 m by 20.6 m plots (0.5 ha) was implemented at each site (Ebel 2006). Snakeweed and grass yield data were collected from 1990 through 2005 in treated and control plots at the end of each growing season. Standing crop estimates were made in ten 31.5 cm by 61 cm quadrats permanently marked with stakes and placed along each of the two transects located diagonally across each plot. Ebel (2006) provides additional detail about the double sampling procedure used and how the samples were corrected to a dry-weight basis.

It should be noted that end-of-season grass yield estimates may not represent growth during only a particular growing season, because the area was not grazed and standing vegetation may persist for several years. The carryover of grass from earlier more productive years was especially noted during periods of drought. As grass yield data was gathered during drought years, like 2000, the researchers realized that some of the grass was likely not produced that year (personal communication with Dr. Kirk C. McDaniel, June 2, 2006). This is a source of potential measurement error.

Figures 1 and 2 show the various treatments implemented through time at the two study sites. Different plots within each site are shown by rectangular boxes in the figures. The numbers at the middle of the boxes indicate the treatment numbers and the numbers at the upper right-hand corner indicate the plot number. The treatment



Treatment Key:

Core Plots

1 Plot #

4 Treatment #

CR-10 Weather Station

0 = Control90
1 = SpBurn90
2 = SuBurn90
3 = Herb90
4 = SpBurn91
5 = SuBurn91
6 = Herb91
7 = SpBurn91 Herb92
8 = SpBurn91, 93, 96, 98, 03
9 = SpBurn93, 03

10 = Control93
12 = SpBurn91, 98
13 = No Treatment
14 = SuBurn91, 96, 03
15 = SuBurn91, Cont.
16 = SpBurn96
17 = SpBurn91, Cont
18 = SpBurn03

Source: Ebel (2006)

Figure 1. South House plot layout for treatments.

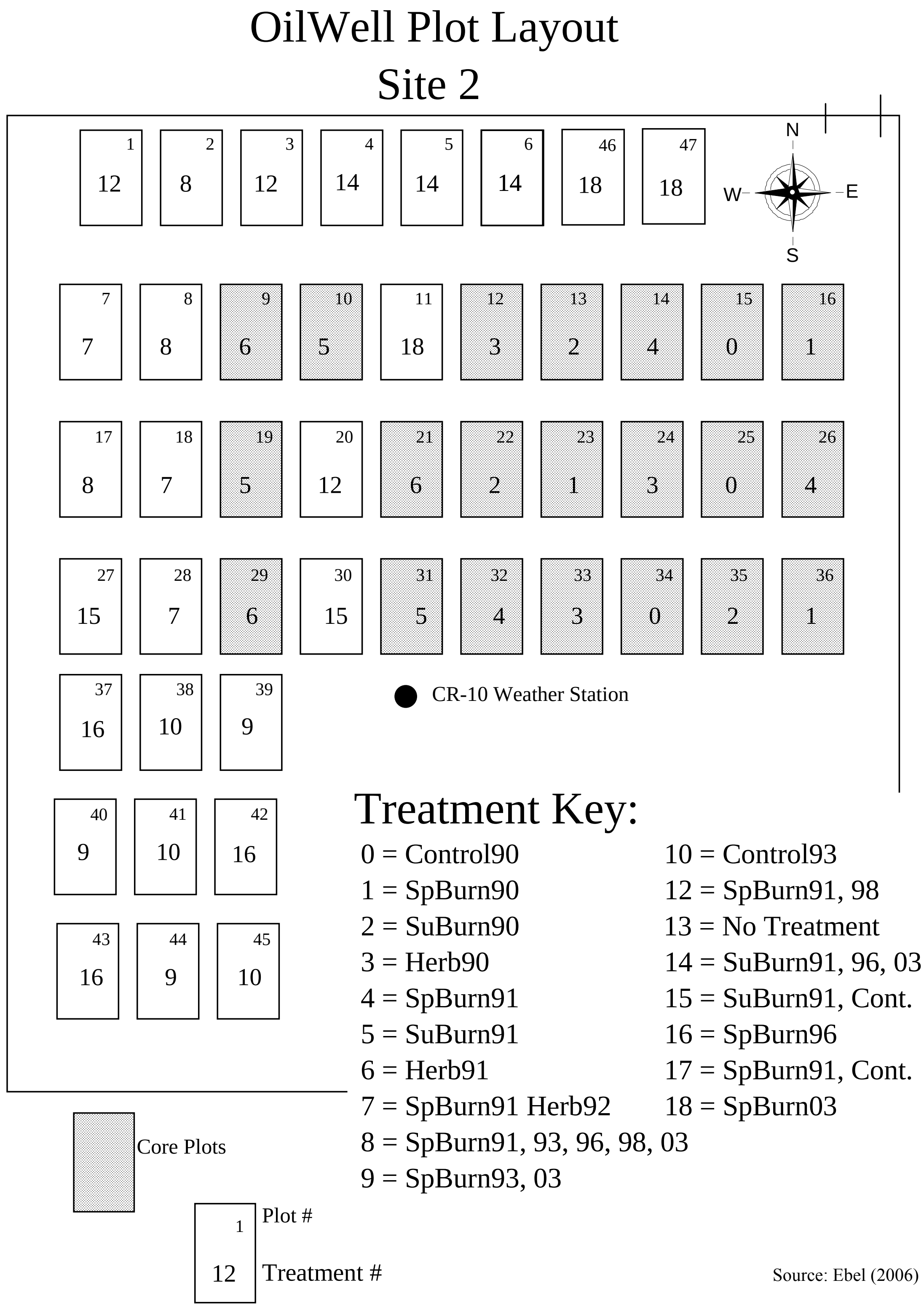


Figure 2. Oil Well plot layout for treatments.

key describes the season and year of application and the type of a particular treatment. For example, the treatment key “1=SpBurn90” indicates that Treatment 1 was a burning treatment applied in spring of 1990. Similarly, “4=SpBurn91” indicates that Treatment 4 was a burning treatment applied in spring of 1991. The treatment key “7=SpBurn91 Herb92” implies that Treatment 7 was a burning treatment implemented in the spring of 1991 plus a herbicide treatment in spring of 1992.

Burning treatments implemented at the study sites were not included in this overstory-understory study because, as noted by Ebel (2006), most burn treatments reduced the following growing season grass yield to some extent and repeat fire treatments reduced grass yield over the long term. Herbicide treatments were very successful in reducing snakeweed populations and subsequently increasing grass yield that was previously suppressed by the shrub. This study considered only the untreated or control areas and herbicide treatments. These include treatments numbered 0, 3, 6, 10, and 13 in Figure 1 and Figure 2.

Figure 3 gives annual average grass and snakeweed yield measured for herbicide-treated plots and untreated areas. Appendix B gives yield estimates by year, site, treatment, and plot number. The pairings of grass and snakeweed yield reported in Appendix B were the data used in the regression analysis. These data are also included on the compact disk (at the sheet “Pivot1” in the Excel file “Yield.xls”).

In 1990 when snakeweed control studies were initiated, snakeweed production and density at both study sites were at levels considered detrimental to grass production (Hart 1992). Herbicide treatments resulted in an immediate reduction in

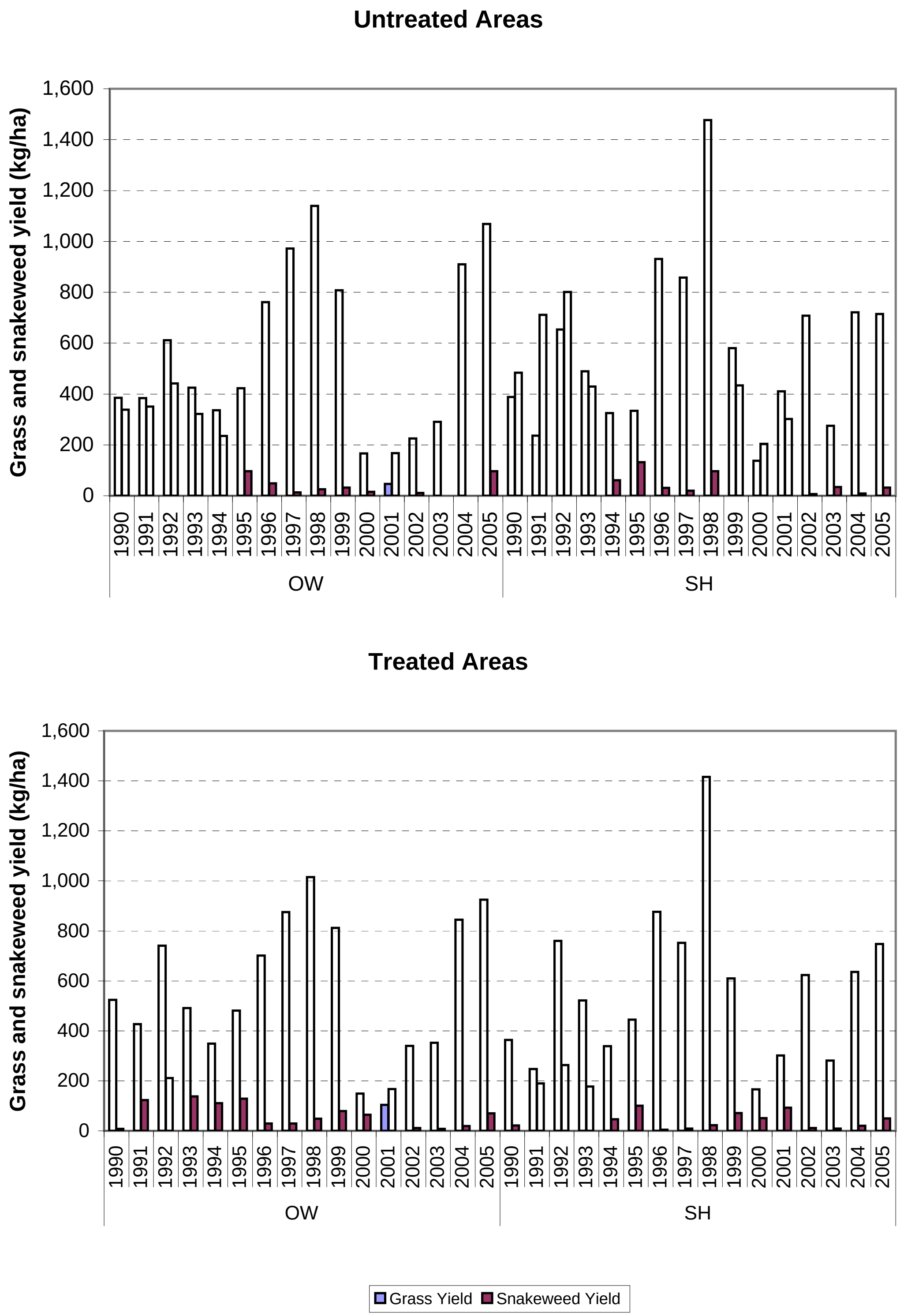


Figure 3. Annual average grass and snakeweed yield (kg/ha) at the Oil Well (OW) and South House (SH) sites, 1990 through 2005.

snakeweed yield and increase in grass yield (Appendix B). However, as the study progressed, snakeweed yield also declined from natural mortality within untreated areas (Appendix B). Snakeweed production was generally low on both treated and untreated areas after 1993.

Regression Equations

The main objective of this research is to relate annual forage production to key weather and environmental factors. Ideally, error-free and continuous recordings of weather data including air temperature, soil temperature, rainfall amounts, and soil moisture measurements would be used to evaluate how herbaceous production varied with key weather related measurements. However, weather measurements were not taken on-site for all years that forage production data were recorded (1990 through 2005) and recording devices did not always function properly. As noted earlier, only 85% of the hours had apparent valid recordings of air temperature, soil temperature, and rainfall once the data loggers were in place. Further, soil moisture probes recorded data starting in 2001 and there were gaps in this data. To fill in the data gaps required estimates for missing values be made. To do this, regression equations were developed for predicting daily changes in soil moisture from rainfall occurrences and other weather related factors.

The soil moisture probes recorded hourly, with periodic interruption, from September 28, 2001 until April 18, 2006. To provide an evaluation of the predictive power of regression equations developed to fill in the data gaps, data recorded after

July 1, 2005 were not used when estimating the regression equations. Recorded data over this later period (July 1, 2005 to April 18, 2006) were used for an out-of-sample comparison of predicted versus actual values. The R^2 for this out-of-sample comparison was calculated from the correlation coefficient computed between actual and estimated values.

Soil Moisture Equations

Solar energy is the major determinant of evapotranspiration. The evapotranspiration process mainly occurs during the day with nighttime conditions affecting soil moisture very little. For this reason, hourly diurnal readings of all weather variables, except precipitation, were averaged each day and used to predict changes in soil moisture. Diurnal values were defined as weather variable recordings made between 6:00 A.M. and 6:00 P.M.

Soil temperature is an important variable influencing the seasonality of soil moisture variation. Soil moisture is depleted quickly during the heat of the summer. Because measurements of soil temperature were missing in some cases a soil temperature regression equation was also estimated. A description of all the variables used in the estimation of soil temperature and soil moisture is given in Table 1. When estimates of air temperature and relative humidity were not available, which was primarily in 1990-91 before weather stations began recording at the study sites, average values for the missing days were used, measured on that day across all other years.

Table 1. Description of variables used in regression equations.

Variable name	**Description**
ATD_t	Average diurnal air temperature (^{0}C) on day t.
STD_t	Average diurnal soil temperature (^{0}C) at 10 cm on day t.
$SM1_t$	Soil moisture at surface 10 cm recorded at 12:00 A.M. on day t
$SM2_t$	Average soil moisture between 10 cm and 30 cm recorded at 12:00 A.M. on day t
$SM1DIF_t$	$SM1_t$ - $SM1_{t-1}$
$SM2DIF_t$	$SM2_t$ - $SM2_{t-1}$
$STSM1_{t-1}$	STD_{t-1} * $SM1_{t-1}$
$STSM2_{t-1}$	STD_{t-1} * $SM2_{t-1}$
RHD_{t-1}	Average diurnal relative humidity at day t-1
$RHAT_{t-1}$	RHD_{t-1} * ATD_{t-1}
$RAIN_t$	Total rainfall (mm) at day t
$RAINDUM_{t-1}$	A dummy variable that is equal to 1 when it rained more than the estimated "knot" (RAINKNOT) at day t-1, and 0 otherwise (the knot is a parameter to be estimated).
$RAINDUMM_{t-1}$	($RAIN_t$ – RAINKNOT) * $RAINDUM_{t-1}$
$RAINSM1_{t-1}$	$Rain_{t-1}$ * $SM1_{t-1}$
$RAINSM2_{t-1}$	$Rain_{t-1}$ * $SM2_{t-1}$
DSITE	Intercept-shifter dummy variable (=1 if site=Oil Well, =0 otherwise)

A cubic polynomial regression model of the following functional form was used to estimate average daily diurnal soil temperature.

$$STD_t = \beta_1 + \beta_2 STD_{t-1} + \beta_3 STD_{t-1}^2 + \beta_4 STD_{t-1}^3 + \beta_5 ATD_t + \beta_6 ATD_t^2 + \beta_7 ATD_t^3 + \beta_8 DSITE + \beta_9 RAIN_t + u \qquad (1)$$

The cubic function recognizes that daily changes in soil temperature are expected to be greater when higher air and soil temperatures are realized. A dummy variable for site (DSITE) was included to test for site differences, and if significant this may reflect calibration differences between the two temperature recording devices located at the alternative study sites. The temperature recorders buried at 10 cm were used for the regression and for other soil temperature measurements included in the soil moisture analysis.

Two different soil moisture measurements, soil moisture measured at a depth of 10 cm from the surface (SM1) and the average soil moisture between 10 cm and 30 cm (SM2), were analyzed using different regression model specifications. The differences between soil moisture at midnight of a particular day and the soil moisture at midnight of the previous day were calculated both for SM1 and SM2, and these differences (SM1DIF and SM2DIF, respectively) were used as dependent variables in models for estimating daily changes in soil moisture. Midnight (12:00 AM) is the starting point of a particular day. Thus, the weather conditions of the previous day (t-1) determine the change in soil moisture between the two midnight readings.

Two separate regression equations were estimated for soil moisture depending on whether it rained. Soil moisture measurements would be expected to increase on days when it rained (rain days) and to decline or remain unchanged if it did not rain (no rain days). It would also be expected that larger rainfall events would increase soil moisture more. Recognizing the expected increase from larger storms a spline model was used to analyze the relationship between rainfall and soil moisture for rain days. Other polynomial functional forms were also initially evaluated. Splines are generally defined to be piecewise polynomials of degree n whose function values and first (n-1) derivatives agree at points where they join (Freund and Littell 2000). The abscissas of these joining points are called knots. Splines for which the values of the independent variable are known for the join points are called “splines with known knots”. Splines with known knots can be estimated by linear regression methods, but estimation of spline models with unknown knots, as in this case, requires the use of nonlinear methods. The nonlinear regression procedure PROC NLIN in SAS (Freund and Littell 2000) was applied to estimate the unknown knot model for rain days.

Various alternative models were initially considered. Variables used in estimating soil temperature and soil moisture are defined in Table 1.The final functional form selected for estimating changes in soil moisture for rain days was:

$$\begin{aligned} SM1DIF_t = {} & \beta_1 + \beta_2 RAIN_{t-1} + \beta_3 RAINDUMM_{t-1} + \beta_4 STSM1_{t-1} + \beta_5 RAINSM1_{t-1} \\ & + \beta_6 RHAT_{t-1} + \beta_7 DSITE + u \end{aligned} \tag{2}$$

A similar model was estimated for changes in average soil moisture between 10 cm and 30 cm with appropriate substitution of data from the deeper probe (SM2). Soil moisture levels are expected to increase with an increase in rainfall ($RAIN_{t-1}$). And, if $RAIN_{t-1}$ is greater than the estimated knot (RAINKNOT) it is expected to mean a higher marginal increase in soil moisture. That is to say, a more significant rainfall event should more thoroughly soak into the ground and be a more significant factor in increasing measured soil moisture. In equation 2, β_2 measures the change in soil moisture influenced by daily rainfall less than RAINKNOT. The estimated change in soil moisture due to rainfall when it is an amount greater than RAINKNOT is $\beta_2 + \beta_3$.

Two interaction terms were used as explanatory variables in the soil moisture difference equation so as to consider the joint effects of those variables. The higher the soil moisture level at the beginning of the day, the higher would be the potential for soil moisture to decline, as influenced by plant transpiration, percolation, and higher soil temperature. Given this, the change in soil moisture (SM1DIF or SM2DIF) would be less the lower is initial soil moisture, and thus β_4 is expected to be negative. Similarly, the higher the soil moisture level the previous day, the lower would be the potential for the soil moisture level to go up as a result of a rainfall event, and the expected increase in soil moisture would be less. If relative humidity was high, soil moisture would be expected to be less influenced by air temperature.

If there was no rain on the previous day, soil moisture is expected to either remain the same or decrease. Noise with the probes and data loggers caused probe measurements to increase by minimal amounts, even though it did not rain, on about 350 days of the 2,918 daily recordings made. To adjust for this apparent measurement error a censored regression model, or a tobit model (Greene 1997), was used to estimate $\mathrm{SM1DIF_t}$ and $\mathrm{SM2DIF_t}$ on “no rain days”. The dependent variable ($\mathrm{SM1DIF_t}$ or $\mathrm{SM2DIF_t}$) was censored with an upper bound of zero and any value greater than zero was reset to zero. The procedure PROC QLIM in SAS (SAS Institute Inc. 2004) was applied to estimate $\mathrm{SM1DIF_t}$ and $\mathrm{SM2DIF_t}$ using the following functional forms.

<u>SM1</u>$_\mathrm{t}$

$$SM1DIF_t^* = \beta_1 + \beta_2 STD_{t-1} + \beta_3 STSM1_{t-1} + \beta_4 RHD_{t-1} + \beta_5 RHAT_{t-1} + \beta_7 DSITE + u \qquad (3)$$

$$SM1DIF_t^* = 0 \qquad \text{if } SM1DIF_t > 0$$
$$SM1DIF_t^* = SM1DIF_t \qquad \text{if } SM1DIF_t \leq 0$$

<u>$SM2_t$</u>

$$SM2DIF_t^* = \beta_1 + \beta_2 STD_{t-1} + \beta_3 STSM2_{t-1} + \beta_4 RHAT_{t-1} + \beta_5 DSITE + u \tag{4}$$

Transformed data ($SM1DIF_t^*$ and $SM2DIF_t^*$) is set to zero if the original data ($SM1DIF_t$ and $SM2DIF_t$) is greater than zero.

Soil moisture was believed to decline faster with higher soil temperatures, capturing both the effect of the added heat in the soil and the transpiration of water by plants during the growing season. Although lagged diurnal relative humidity was used to explain the variability in $SM1DIF_t$, it was determined to not be important in the model for estimating $SM2DIF_t$. $SM1_t$ was measured at only 10 cm from the soil surface whereas the second probe was deeper, from 10 cm to 30 cm, and this likely explains the insignificance of relative humidity for SM2DIF. Relative humidity was found to significantly influence evapotranspiration only for the shallower probe.

Statistical significance of the dummy variable DSITE would mean there was a systematic difference between the volumetric soil moisture measurements taken by the probes at the two sites, and regression results determined this to be the case. It was likely a result of probe calibration difference; one or both of the soil moisture probes did not accurately measure volumetric soil water content. When using the soil moisture measurements to predict herbaceous grass production, adjustments were made to the soil moisture measurements recorded or predicted at the Oil Well site so that average measurements were the same as those recorded by the same probe at the

South House site. This was done by running a regression without an intercept term between soil moisture measurements at the South House (SH) site versus those at the Oil Well (OW) site. It was determined that the Oil Well SM1 probe recorded values that were 20% more than at South House, and SM1 values were adjusted down by this amount. Soil Moisture values for probe 2 were adjusted up by 6% for the Oil Well site. This adjustment puts the soil moisture recordings at the two sites on the same scale. Without additional calibration of the probes it is uncertain which probe accurately measures volumetric soil moisture, or if either one does.

Herbage Production Equations

Equations similar to the sigmoidal equation used by McDaniel et al. (2005), and applied earlier by McDaniel et al. (1993) to relate understory grass yield to overstory canopy cover were used for estimating herbage production. Jameson (1967) originally proposed this sigmoidal growth curve as an appropriate general model for defining overstory-understory relationships. General specification of the sigmoidal growth curve used by McDaniel et al. (2005) was:

$$Y = H + H_P D + (A + A_P D)(1 - e^{-BX})^M \qquad (5a)$$

Model variables were defined to be:

Y = perennial grass yield (kg/ha)

X = brush overstory

D = a dummy variable (D=1 during years when grass yield was above average, D=0 during below-average years)

H, H_P, A, A_P, B, and M are model parameters estimated using nonlinear regression.

This functional form is flexible and unique because, depending on the values of estimated parameters, the shape of the curve can range from sigmoid to exponential, which are the common shapes defined for overstory-understory relationships (Ffolliot and Clary 1972). The curve decreases exponentially when M is less than 1, and the length of the flat upper asymptote increases when M increases above 1. The curve has a sigmoid or S-shape for M>1 when grass yield is plotted against brush overstory. When M=1, the equation reduces to an exponential function. In the McDaniel et al. (2005) specification of the regression equation, the dummy variable D shifts the curve up during above average grass production years. The parameter H_P shifts the intercept (H) and the parameter A_P shifts the parameter A during above-average years. H+A defines the lower asymptote for below-average years, and $H+H_P+A+A_P$ defines the lower asymptote during above-average years (McDaniel et al. 2005).

Modifications to equation 5a were made to incorporate rainfall and soil moisture as the asymptote shifters instead of the less desirable dummy variable. The equation is, in concept, easily modified by replacing D with some continuous variable (MOIS) that measures moisture and environmental conditions over the year. Different models were estimated where the variable measuring moisture was considered to be either rainfall or soil moisture. With this adjustment equation 5a becomes:

$$Y = H + H_P \mathrm{MOIS} + (A + A_P \mathrm{MOIS})(1 - e^{-BX})^M \qquad (5b)$$

Average yearly grass and snakeweed production data for each of the two study sites, classified by treatment applied and plot number (Appendix B), were used in estimating the herbage production equations. Average air temperature, soil moisture, and rainfall measured over alternative months and seasons were considered as potential explanatory variables in the final models and in other models initially estimated. The amount of broom snakeweed (kg/ha) was included as an explanatory variable. Alternative functional forms for environmental influences were also considered. First, rainfall amounts measured over alternative seasons were considered as the MOIS variable in equation 5b. Second, the calculated number of days over the year when soil moisture and air temperature were adequate for grass production was considered.

Definition of the number of desirable growing days required a two-step procedure. Stubbendieck and Burzlaff (1970) identified 10^{o}C as a critical minimum temperature for the growth of blue grama. The number of days in the year where average daily diurnal temperature exceeded this critical level was estimated. Only the months of March through October were considered as potential periods for computing desirable temperature, assuming any days during the other winter months would be inconsequential for the production of warm season grasses. November was excluded because of cool and declining daily air temperatures, and because grass yield clippings were usually taken by mid-November.

A critical level of minimum soil moisture was established through an iterative process when estimating the regression model. The hypothesis was that maintaining soil moisture above some critical level was required for grass production, coupled with the condition that average daily diurnal air temperature must also exceed 10^{o}C.

This critical point for soil moisture is unknown. Therefore, using the adjusted data (adjusted to be on the same scale for both study sites) from each of the soil moisture probes separately, an initial and somewhat arbitrary estimate was made that volumetric soil moisture measured by the probe needed to exceed 30% for grass growth to occur that day. The number of days when soil temperature exceeded $10^{o}C$ and soil moisture was greater than 30% was tabulated and the regression model estimated using this day count as the MOIS variable. The regression model was then re-estimated for a slightly lower or higher critical point for soil moisture and the sum of squared errors (SSE) was computed. Through this iterative process the critical soil moisture level was determined to be the soil moisture cutoff level where SSE was minimized. A similar procedure was used for both probes.

A description of all the variables used in the herbage production equation is given in Table 2. The estimated equations are given by:

Table 2. Description of variables used in herbage production equation estimation.

Variable name	**Description**
GRASS	Grass yield (kg/ha)
GUSA	Snakeweed yield (kg/ha)
GROWDAYS1	Total number of days during March through October of a year when both soil moisture at 10 cm and average diurnal air temperature were greater than the critical minimum level required for grass production.
GROWDAYS2	Total number of days during March through October of a year when both soil moisture between 10 cm and 30 cm and average diurnal air temperature were greater than the critical minimum level required for grass production.
RAINQ1	Total rainfall in quarter 1.
RAINQ2	Total rainfall in quarter 2.
RAINJULOCT	Total rainfall in the months of July, August, September, and October.

Model 1: $$\mathrm{GRASS} = \mathrm{H} + \mathrm{H_P GROWDAYS1} + (\mathrm{A} + \mathrm{A_P GROWDAYS1})(1 - e^{-B^{*}GUSA})^{M} + u \quad (6)$$

Model 2: $$\mathrm{GRASS} = \mathrm{H} + \mathrm{H_P GROWDAYS2} + (\mathrm{A} + \mathrm{A_P GROWDAYS2})(1 - e^{-B^{*}GUSA})^{M} + u \quad (7)$$

Model 3: $$\mathrm{GRASS} = \mathrm{H} + \mathrm{H_{P1} RAINQ1} + \mathrm{H_{P2} RAINQ2} + \mathrm{H_{P3} RAINJULOCT} + (\mathrm{A} + \mathrm{A_P RAINJULOCT})(1 - e^{-B^{*}GUSA})^{M} + u \quad (8)$$

Valuing Water

The economic value of water was estimated as the monetary value of the estimated changes in forage production resulting from additional rainfall events of different magnitudes and with different timing within the year for the South House study site. Fitted soil moisture and grass yield equations were used to estimate the change. Soil moisture probe 2 (Model 2) was not considered in the valuation because the estimated forage response was similar to that estimated using Model 1.

To compare forage response and economic value from rainfall events between dry and wet years, 2003 and 2004 were chosen. The 2003 production year was one of the driest years over the study period and 2004 was an above average rainfall year. Comparison was also made between low and high snakeweed infestations by assuming a level of snakeweed production of 0 and 300 kg/ha, respectively, when estimating grass yield.

The number of growing days in a year was determined as the number of days from March through October when soil moisture and air temperature were greater than the critical minimum air temperature level of 10^oC and the minimum level of soil moisture (at 10 cm) that was iteratively determined, as described above.

In computing the number of growing days, predicted values of lagged soil moisture were used and lagged values were not replaced with actual recorded values when available. This procedure was followed because the altered soil moisture state with added rainfall amounts must be compared to the similarly predicted state without the rainfall amounts.

Soil moisture was first estimated over the 2003 and 2004 production years using the rainfall events that actually occurred over the period. Then additional rainstorms were assumed to occur at different dates and of different magnitudes and the modified level of soil moisture was used to estimate a new day count. Rainfall events of 6.4 mm (0.25 in), 13 mm (0.5 in), and 25.4 mm (1 in) were considered to occur, each as a separate analysis, on the first day of February, April, May, and July. A 25.4 mm rainfall is a rare occurrence on the Corona Ranch. Thus, it should be noted that a rainstorm of this magnitude would be equivalent in its impact on soil moisture to a series of wet days with total rainfall of 25.4 mm.

Because equation 2 was used to predict the altered level of soil moisture for all days, given only the starting value of the series on January 1, 2003, the growing day counts used in valuing water were different when actual soil moisture levels did not adjust the predictions. The South House soil moisture chart included in the compact disk (at the sheet “SH_CHART” in the Excel file “Soil Moisture1.xls”) shows the difference in estimated soil moisture over the 2003-2004 period with the alternative prediction procedures.

In addition to using Model 1 to value storms by considering an altered level of soil moisture, the rainfall model (Model 3) was also used to directly value the rainfall event by computing new seasonal rainfall totals that would occur with the added rain. Rangelands are not irrigated. Thus the economic value of additional grass produced from a rainfall event reflects the marginal value of that storm. According to Bartlett et al. (2002), a reasonable estimate of net forage value is about 70% of the average USDA reported lease price for rangeland forage. Recent lease rates have been about \$13.70/AUM[1] (USDA- NASS 2005). Thus, the economic value of an additional kg of forage was considered to be \$0.026/kg (\$9.59/AUM).

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[1] An AUM (animal unit months) is considered to be the amount of forage required be a mature cow or the equivalent over a 1 month period. An 800 pound (363 kg) AUM was used.

RESULTS

Weather Conditions on the Corona Ranch

This section summarizes weather data collected on the Corona Ranch since the middle of 1991. Off-ranch rainfall data collected from nearby weather stations are also included for 1989, 1990, and part of 1991. The weather database is provided on the compact disk (Corona Weather Data 2006.mdb). The spreadsheet files “Soil Moisture1.xls” and “Soil Moisture2.xls” provide charts with daily measurements and predicted values for key weather variables including diurnal air temperature, diurnal soil temperature, rainfall amounts, soil moisture measurements, and the soil moisture measurements adjusted to the South House scale.

Air Temperature

The Corona Ranch is characterized by a semiarid, continental climate with wide ranges in diurnal and seasonal temperatures. Over the study period, average daily maximum air temperature on the ranch was 9^{o}C (48^{o}F) during December-January and 29^{o}C (84^{o}F) in July. Average daily minimum air temperature was -4^{o}C (25^{o}F) during December-January and 14^{o}C (57^{o}F) in July. The hottest and coldest temperatures recorded over the study period were 39^{o}C (102^{o}F) on June 26, 1994 and -22^{o}C (-8^{o}F) on December 8, 2005. The growing season, or frost-free season, is about 215 days a year, from April 1 to November 1 (Figure 4). Perhaps more important for range forage production, Stubbendieck and Burzlaff (1970) identify 10^{o}C as a critical

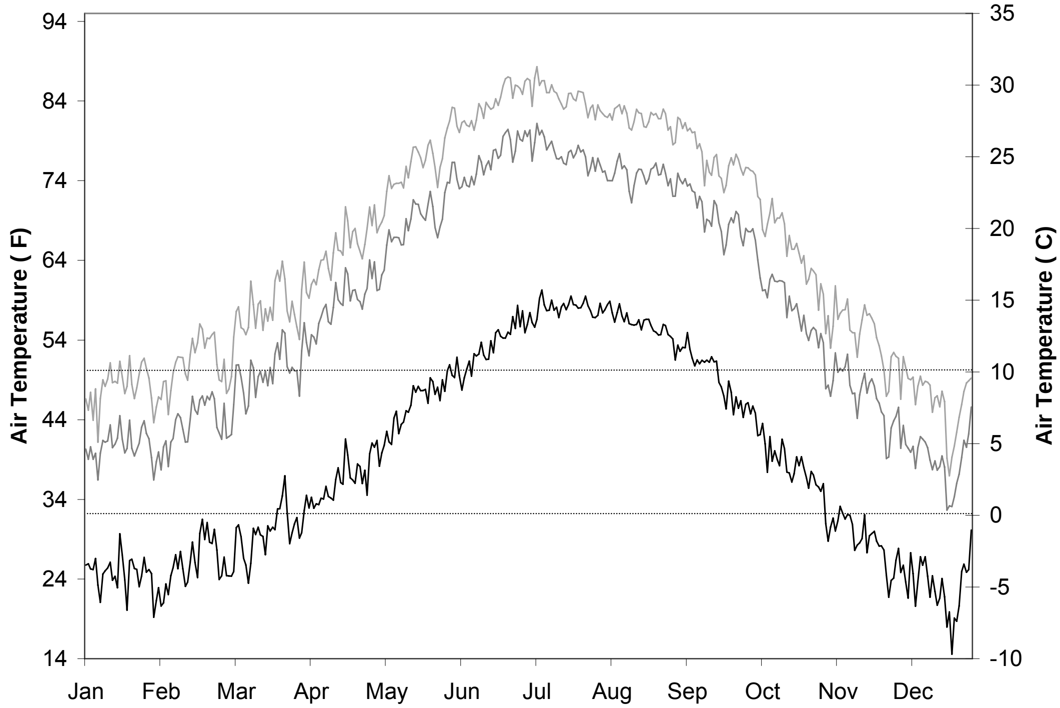


Figure 4. Daily average minimum and maximum air temperature and average diurnal air temperature (July 17, 1990 – April 18, 2006).

minimum temperature for growth of blue grama, the predominant forage species on the Corona Ranch. As shown in Figure 4, average daily diurnal air temperatures (middle curve) begin to exceed 10^{o}C by mid-march and return to this level by the first of November.

Soil Temperature

The recorded daily average soil temperature (at 10 cm) fluctuated annually and daily depending on variation in air temperature and solar radiation (Figure 5). Peak soil temperatures were recorded during the summer of 1999 with several diurnal daily averages exceeding 30^{o}C (86^{o}F) (see daily charts on the compact disk).

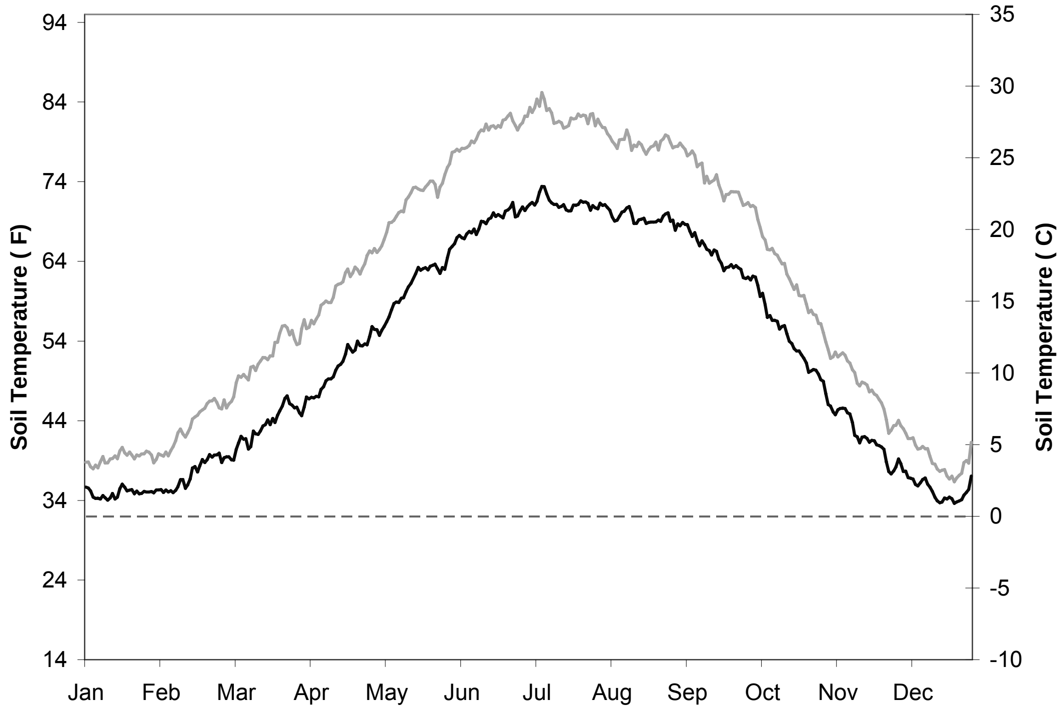


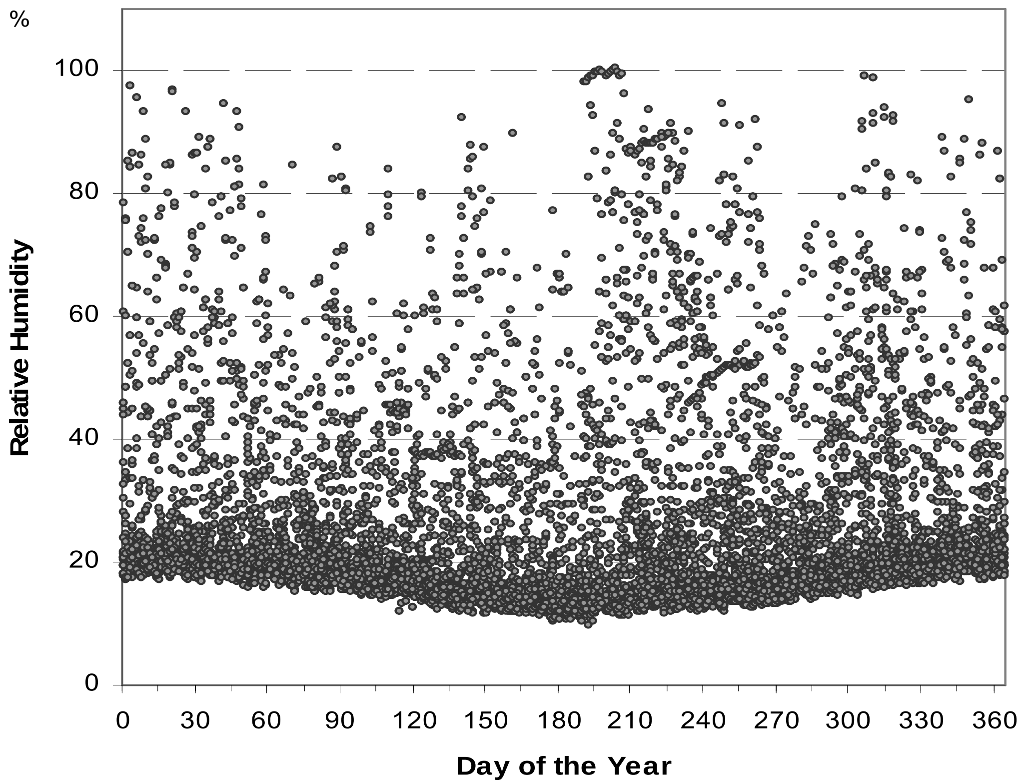
Figure 5. Daily average minimum and maximum soil temperature at 10 cm (July 17, 1990 – April 18, 2006).

Relative Humidity

Relative Humidity varied widely on the Corona Ranch during the study period, ranging from nearly 100% on wet, rainy days to a dry 10% during June (Figure 6). Daily average humidity was most frequently in a narrow range from 12% to 25%. Averaged by month, humidity ranged from 20% to 31%.

Wind Speed and Direction

Figure 7 shows the frequency of different hourly maximum wind speeds at the Corona Ranch and the wind direction, i.e., the average direction (in degrees) that



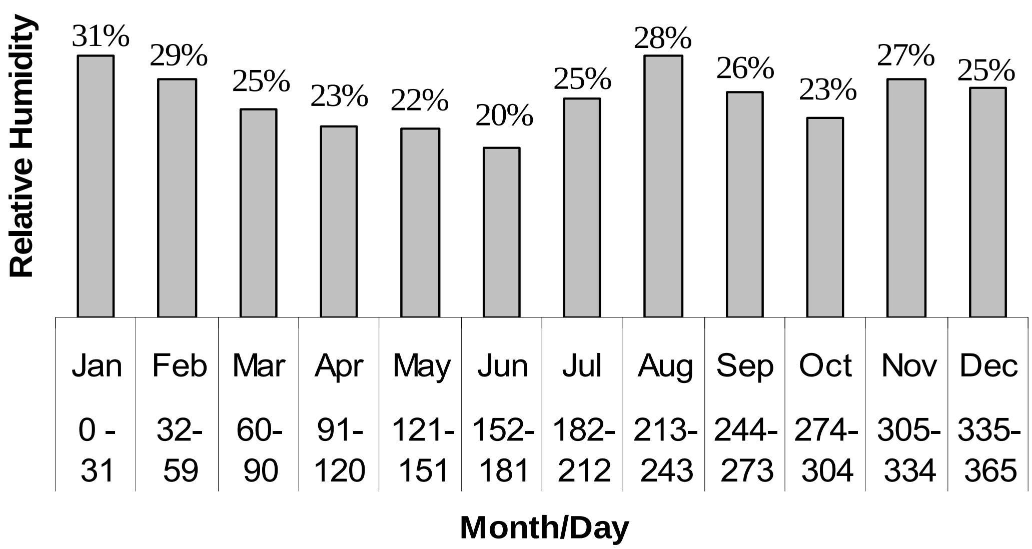


Figure 6. Daily and monthly average relative humidity (July 17, 1990 – April 18, 2006).

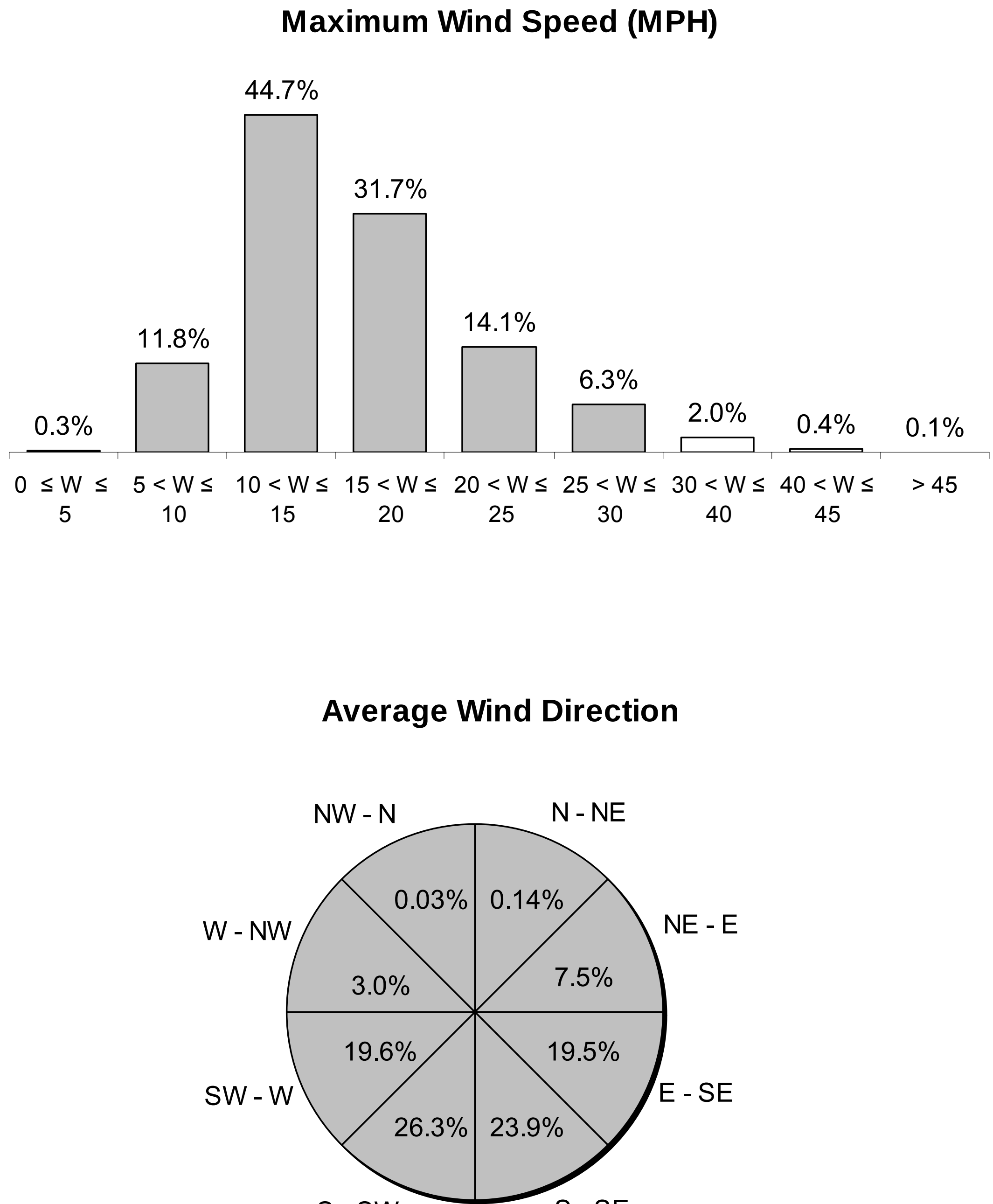


Figure 7. Percentage of hours with different maximum wind speeds, and of hourly average wind directions (July 17, 1990 - April 18, 2006).

wind blows over the day. As shown, wind blows from the south 90% of the time and it blows nearly every day.

Rainfall

Mean annual precipitation at the Corona Ranch averaged 327 mm (12.9 inches) over the 1990-2005 study period (Figure 8). The 30-year annual average rainfall for the Corona Ranch is reported to be 388 mm (McDaniel 2002). Monthly precipitation (mm) from 1990 to 2005 on the Corona Ranch is shown in Appendix D.

Growing season (considered to be quarter 2 and quarter 3) rainfall was above average during 1991, 1992, 1994, 1996, 1997, and 2004. It was near average during 1999 and 2002. An extended drought occurred from late 1999 through 2003 with both growing season and annual rainfall totals at or below average for each of these years.

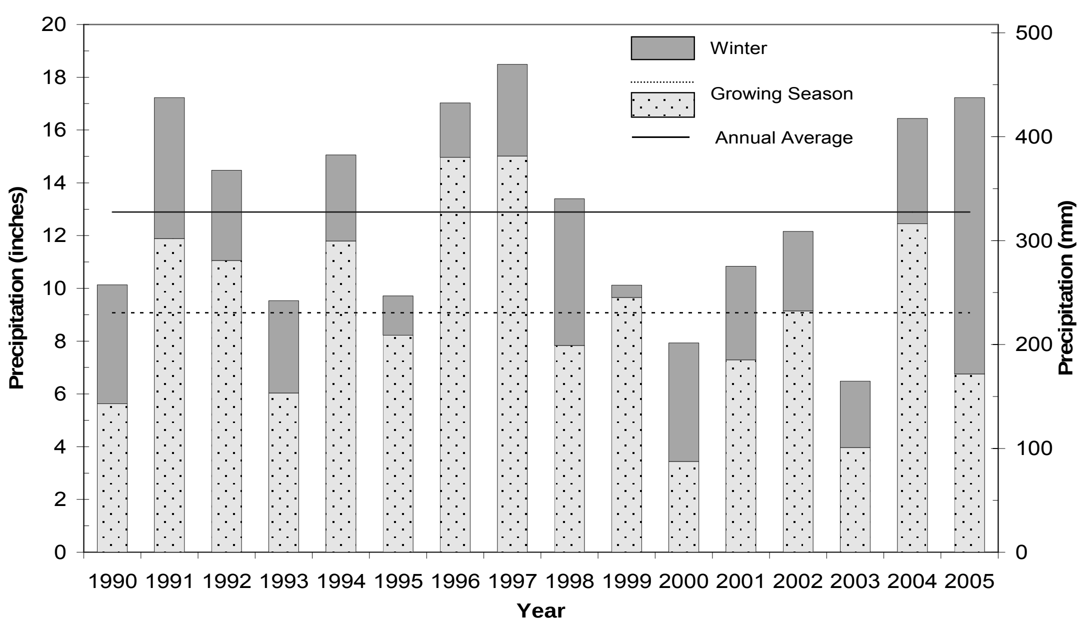


Figure 8. Growing season (April-September) and total annual precipitation at the Corona Ranch, 1990-2005.

The 2004 production year apparently ended the drought, but the relief was short-lived. The 2005 production year was a unique and unusual year with a record amount of winter moisture, but growing season rainfall was well below average. The weather stations at the research sites have recorded less than 3 mm (0.1 inches) of rainfall for the first quarter of 2006. The drought continues.

It is not uncommon on the Corona Ranch to have very long stretches without rain, especially during the winter. The longest period without significant rain occurred during 1995-1996 when it did not rain more than 6 mm (0.25 inches) for 273 days. Similar dry periods occurred during the winter of 1999 and 2000 (see charts on the compact disk file “Soil Moisture1.xls”). A dry period is currently underway with the last significant rain occurring in early October, 2005.

The Corona Ranch has many sunny days. As shown in Figure 9, on 82% of the days of a year (299 days) it did not rain or snow. This percentage is lower during quarter 3 with 71% of the days sunny during this quarter. Much of the annual rain is from localized thundershowers during quarter 3.

When it does rain (on about 66 days of a year), it rains less than 0.25 inches (6.4 mm) 77% of the time. Rain events over the day exceeded 0.50 inches (12.7 mm) about 10% of the time. When it does rain, it rains over 1 inch (25.4 mm) about 3% of the time with these large storms rarely occurring during the fourth quarter.

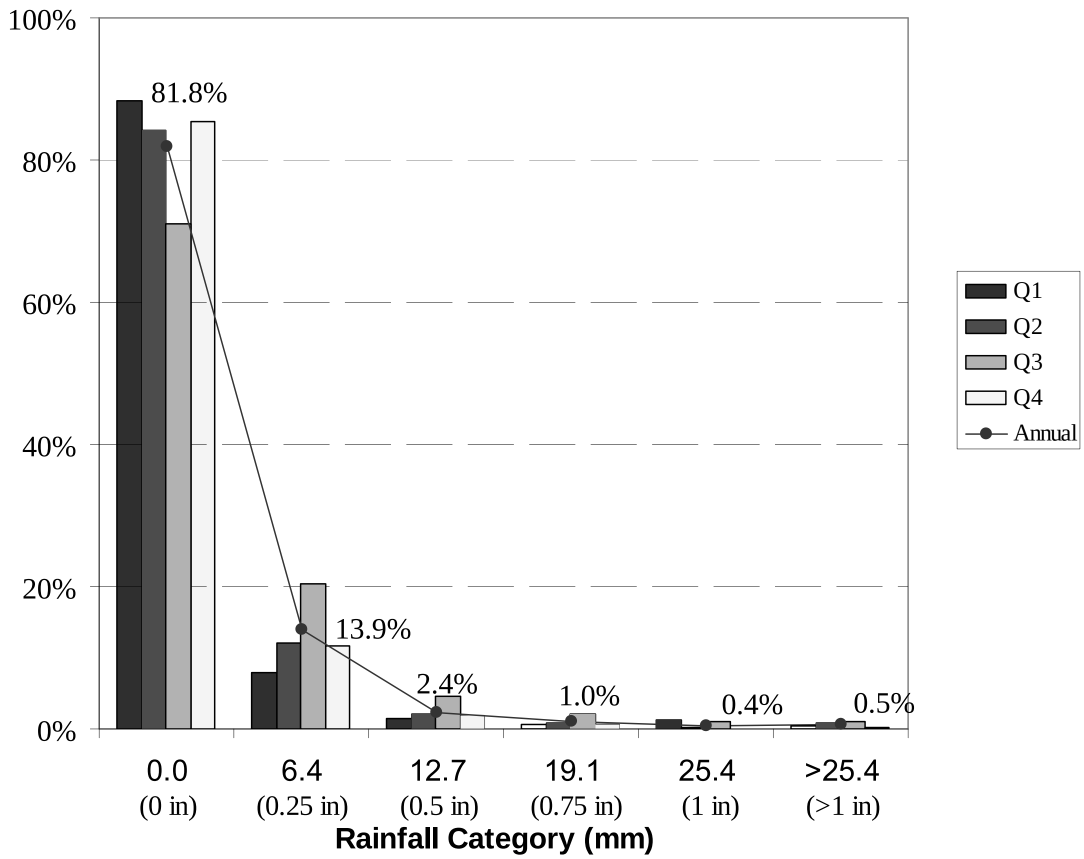


Figure 9. Percentage of days with different amounts of rain (January 1991 - May 2005).

Soil Moisture

Approximately 69,100 hourly recordings of soil moisture at two depths, 10 cm and between 10 cm and 30 cm, were made over about 2,700 days on the Corona Ranch between September 28, 2001 and April 18, 2006. This includes moisture probes located at both the South House and Oil Well research areas. Measured over all quarters 44% of the days had soil moisture at 10 cm (Probe 1) recorded less than 20% by volume (Figure 10). Average soil moisture between 10 cm and 30 cm (Probe 2)

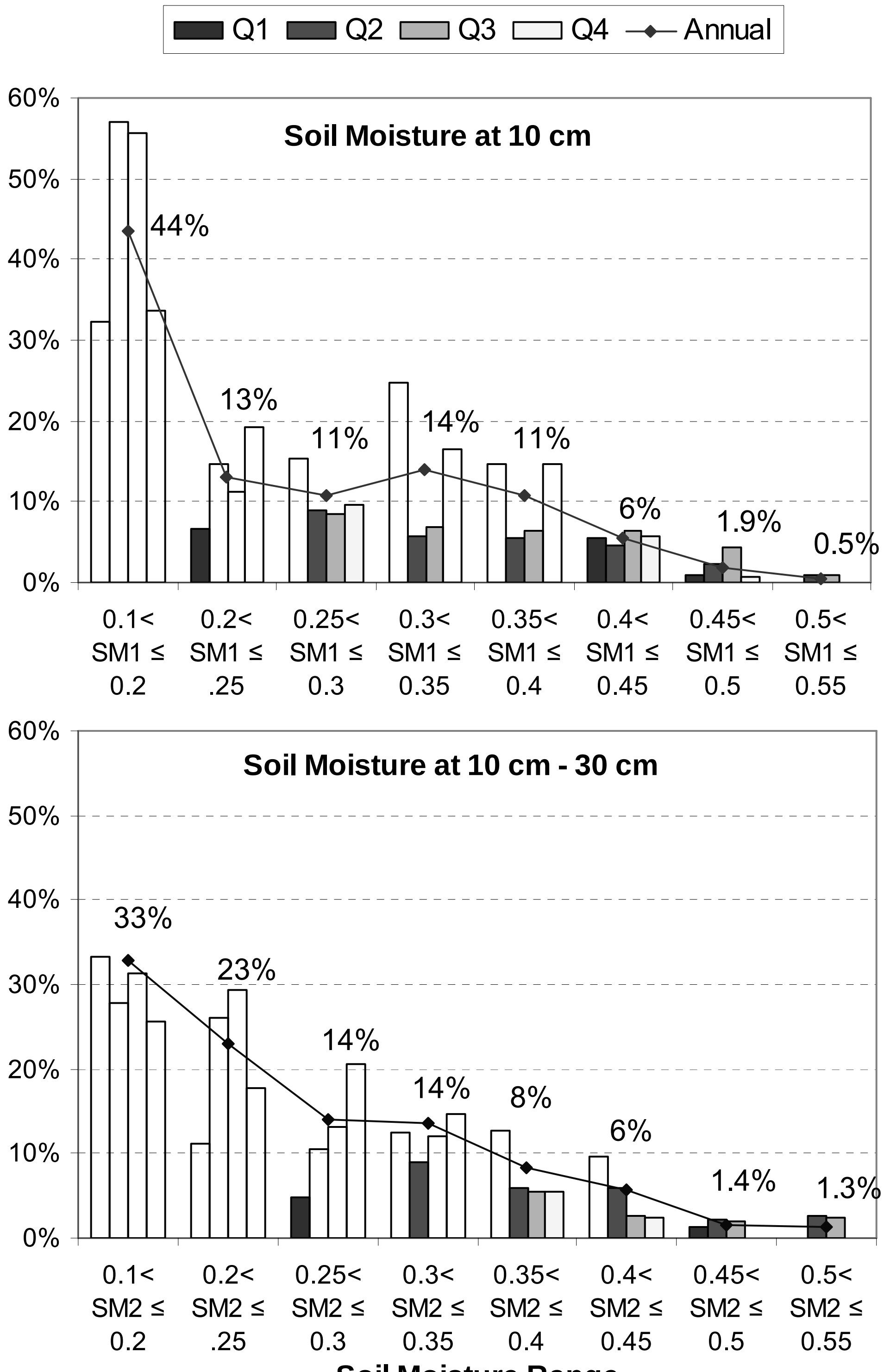


Figure 10. Percent of days with different soil moisture readings measured at midnight at both the Oil Well and South House study sites (Sept. 28, 2001 - April 18, 2006).

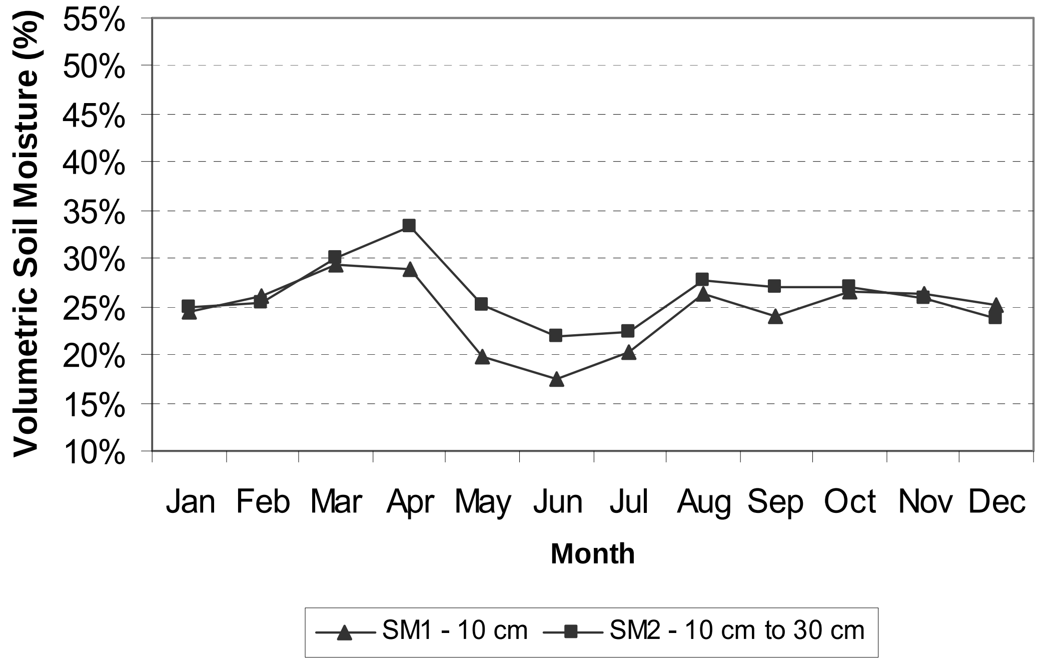


Figure 11. Monthly average soil moisture readings measured at midnight at both the Oil Well and South House study sites (Sept. 28, 2001 - April 18, 2006).

was less than 20% by volume for 33% of the days. Frequency of dry soil was higher during quarter 2 and 3 when plants transpire and temperatures are high. Saturated, wet soil was very uncommon with only about 2.5% of the days (about 9 days) recording soil moisture greater than 45% by volume, both at 10 cm and between 10 cm and 30 cm. Both of the probes recorded with a similar seasonal trend (Figure 11). But, as would be expected, the deeper probe (10-30 cm) remained at higher levels during the hotter summer months.

Soil Moisture Estimation

The cubic polynomial regression model used to estimate soil temperature (equation 1) accounted for 99% of the variation in daily movements of diurnal soil temperature. The root mean square error from the regression was 0.79°C. The results of this estimation process are shown in Table 3.

Differences between the two soil temperature recorders are noted with the significance of DSITE. Rainfall over the day reduced the daily change in soil temperature, with each additional mm of rainfall reducing soil temperature by 0.02°C. The calculated value of the Durbin-Watson statistic was 1.91 which did not indicate a problem with autocorrelation.

The soil temperature equation was used to estimate soil temperature 1,944 times when recorded soil temperature was not available at the particular study site. This represented 16% of occurrences when estimates of soil temperature were needed. The equation was primarily used for the years prior to the establishment of the weather stations in 1990.

Table 3. Daily change in soil temperature regression equation.

Parameter	**Variable**	**Parameter Estimate**	**Standard Error**
β_1	*Intercept*	-0.30159	0.02944
β_2	STD_{t-1}	0.85781	0.00842
β_3	STD_{t-1}^2	-0.00353	0.00062
β_4	STD_{t-1}^3	0.00011	0.00001
β_5	ATD_t	0.11123	0.00337
β_6	ATD_t^2	0.00623	0.00031
β_7	ATD_t^3	-0.00015	0.00001
β_8	*DSITE*	0.20961	0.01617
β_9	$RAIN_t$	-0.02229	0.00241

R^2	=	0.99
n	=	10102
Mean of dependent variable	=	14.18
Root mean square error	=	0.79
Durbin Watson d Statistic	=	1.91

Note: All coefficients are statistically different from zero at 0.01% level.

Fitted nonlinear spline models for "rain days" explained 68% of the in-sample variability in $SM1DIF_t$ and 75% of the variability in $SM2DIF_t$. Table 4 shows the results of these regressions. The 'knot' in rainfall was estimated to be 6.55 mm for $SM1DIF_t$ and 9.91 mm for $SM2DIF_t$.

If rainfall was below 6.55 mm, then each 1 millimeter increase in rainfall on the previous day caused, on average, $SM1DIF_t$ (Probe 1) to increase by 0.0076 units, holding other variables constant. But, if rainfall was above 6.55 mm, for each one unit increase in rainfall, $SM1DIF_t$ increased by 0.0134 (0.0076+0.0058) units. Similarly, for probe 2, if rainfall was below 9.91 mm, then each 1 millimeter increase in rainfall on the previous day caused, on average, $SM2DIF_t$ to increase by 0.0049 units. But if

Table 4. Regression for estimating soil moisture changes for "rain days".

		$SM1DIF_t$		$SM2DIF_t$	
Parameter	**Variable**	**Parameter Estimate**	**Standard Error**	**Parameter Estimate**	**Standard Error**
β_1	*Intercept*	-0.00422	0.00412	-0.00105	0.00242
β_2	$RAIN_{t-1}$	0.00758	0.00121**	0.00485	0.00061**
β_3	$RAINDUMM_{t-1}$	0.00582	0.00115**	0.00507	0.00054**
β_4	$STSM1_{t-1}$	-0.00003	0.00001*		
β_4	$STSM2_{t-1}$			-0.00002	0.00001*
β_5	$RAINSM1_{t-1}$	-0.00023	0.00002**		
β_5	$RAINSM2_{t-1}$			-0.00013	0.00002**
β_6	$RHAT_{t-1}$	0.00004	0.00002*	0.00003	0.00001*
β_7	*DSITE*	0.00833	0.00350*	0.00179	0.00199
β_8	*RAINKNOT*	6.55030	1.25110**	9.90550	1.02230**
R^2		=	0.68	=	0.75
n		=	434	=	427
Mean of dependent variable		=	0.0156	=	0.0093
Root mean square error		=	0.03	=	0.02

Note: Single and double asterisks (*) denote coefficients are statistically different from zero at 5% and 0.01% levels, respectively. The R^2 was computed as the squared coefficient of correlation between the actual and predicted values of the dependent variable.

rainfall was above 9.91 mm, for each mm increase in rainfall, $SM2DIF_t$ increased by 0.01 (0.0049+0.0051) units.

To estimate $SM1DIF_t$ and $SM2DIF_t$ for 'no rain days' a censored tobit model was used. The results of these regressions are shown in Table 5. On average, $SM1DIF_t$ increased by 0.0005 units and $SM2DIF_t$ by 0.0003 units for every one unit increase in diurnal soil temperature. $STSM1_{t-1}$ had a negative effect on $SM1DIF_t$. Interpretation is that the higher the soil moisture level the day before ($SM1_{t-1}$), the greater the potential for soil moisture to decrease as influenced by soil temperature. $STSM2_{t-1}$ had a similar effect on the deeper probe. For each additional percent of diurnal relative humidity on the day before, $SM1DIF_t$ increased by 0.0003 units. Relative humidity had no significant effect on soil moisture between 10 cm and 30 cm, but it did interact with temperature to slow the daily decrease in soil moisture for both probes.

Table 5. Regression for estimating soil moisture difference for "no rain days".

		$SM1DIF_t$		$SM2DIF_t$	
Parameter	**Variable**	**Parameter Estimate**	**Standard Error**	**Parameter Estimate**	**Standard Error**
β_1	*Intercept*	-0.004417	0.001816*	0.005149	0.000563***
β_2	STD_{t-1}	0.000472	0.000039***	0.000310	0.000052***
β_3	$STSM1_{t-1}$	-0.000045	0.000001***		
β_3	$STSM2_{t-1}$			-0.000037	0.000002***
β_4	RHD_{t-1}	0.000252	0.000081*		
β_5 / β_4	$RHAT_{t-1}$	0.000011	0.000003**	0.000019	0.000004***
β_6 / β_5	*DSITE*	0.004882	0.000328***	-0.001463	0.000413**
R^2		=	0.41	=	0.21
n		=	1,895	=	1,882
Mean of dependent variable		=	-0.0037	=	-0.0024

Note: Note: Single, double, and triple asterisks (*) denote coefficients are statistically different from zero at 5%, 0.1%, and 0.01% levels, respectively. The R^2 was computed as the squared coefficient of correlation between the actual and predicted values of the dependent variable.

The dummy variable for DSITE was statistically significant both for $SM1DIF_t$ and $SM2DIF_t$ implying that soil moisture measurements varied between the two study sites. This difference was systematic and it likely reflects a calibration error. As noted earlier, adjustments were made for these site differences when relating soil moisture to annual grass yield.

To estimate soil moisture an upper bound with saturated soil was considered to be 0.55. Thus, soil moisture measured at 10 cm (SM1) at time t was estimated using equation 9. $S\hat{M}2_t$ was estimated similarly.

$$S\hat{M}1_t^* = SM1_{t-1} + SM\hat{1}DIF_t \tag{9}$$

$$S\hat{M}1_t^* = 0.55 \qquad \text{if } S\hat{M}1_t > 0.55$$
$$S\hat{M}1_t^* = S\hat{M}1_t \qquad \text{if } S\hat{M}1_t \leq 0.55$$

Data after July 1, 2005 were not used when estimating the regression equations. An out-of-sample comparison of predicted versus actual values (combined for rain days and no rain days) was made using the data recorded over this most recent period. The R^2 for this comparison was computed as the squared coefficient of correlation between the actual and estimated values of soil moisture in the out-of-sample period. The estimated R^2 was 0.89 for the soil moisture probe 1 and 0.91 for the deeper probe 2. In this comparison, previous day values used in the difference equation (equation 3) were set to those actually recorded by the data loggers, such that previous-day values were from the actual measurement taken the previous day when available. This is how the equation was used when estimating missing soil moisture measurements within the data series.

Another way to compute predicted changes in a time series model is to set an initial value for the lagged variable and progress forward using the predicted values at each step. This was the procedure used to estimate daily soil moisture before the soil moisture probes were installed. In this case past errors in prediction continue to be manifested in current predictions. When the out-of-sample comparison was made in this way the computed R^2 values were not good, 0.27 for the SM1 prediction and 0.04 for the SM2 prediction. Further evaluation indicated the soil moisture equations, especially the SM2 equation, predicts relatively poorly at low soil moisture levels. With low soil moisture, the daily decline in the moisture index tended to be under estimated and this was the situation for the out-of-sample comparison period.

A relatively high level of confidence might be placed on estimated values once the soil moisture probes were put in place in 2001 and only periodic lapses in the recordings needed to be estimated. Estimates for 1990 through 2001 are suspect given that the actual soil moisture over this period was never known. It can be noted, however, that the procedure used to relate soil moisture to grass yield was to evaluate whether the recorded daily measurement or predicted value exceeded a critical minimum level (Table 2). The prediction accuracy needed to establish this is much lower than that needed to establish the absolute daily level of soil moisture.

Grass Yield Estimation

Critical minimum levels required for grass growth were initially assumed to be 10^{o}C for diurnal air temperature and 30% for volumetric soil moisture content. Regression equations were estimated with altered values for these minimum levels to compare the sum of squared errors (SSE) for each regression. The critical value of soil moisture that minimized SSE was found to be 21% for probe 1 and 38% for probe 2. These levels of soil moisture were used to calculate the number of days during a year when soil moisture and air temperature were both greater than the critical estimated minimum level. Tables 6 and 7 shows the count of days for probe 1 at the two study sites while Tables 8 and 9 gives the counts for probe 2. Three sections are shown in each table. The top section shows how many days in the month had average diurnal air temperature above 10^{o}C. The middle section shows the day count for soil moisture above the estimated critical minimum. The third section combines to show the number of days when both conditions were met.

As shown in the tables, 2000 was generally indicated to be the driest year with, on average, the lowest number of days with adequate temperature and soil moisture for grass production. Based on the 10 cm probe (probe 1), the South House site had only 54 days with adequate temperature and soil moisture (Table 6). The similar day count at Oil Well was 35 days using probe 1 (Table 7) and 7 days with probe 2 (Table 9).

Based on soil moisture measurements, 2003 was another very dry year with none of the days during the year having measured SM2 above the estimated critical

Table 6. Number of days with adequate air temperature and soil moisture at 10 cm at the South House site (1990-2005).

Adequate Air Temperature (>10 degree C)								South House, SM1	
				Month					
Year	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Total**
1990	17	30	31	30	31	31	30	30	230
1991	12	28	31	30	31	31	27	31	221
1992	17	27	29	30	31	31	30	31	226
1993	13	24	30	30	31	31	30	24	213
1994	17	24	29	30	31	31	30	26	218
1995	16	18	30	30	31	31	28	30	214
1996	16	25	31	30	31	31	30	23	217
1997	22	16	30	30	31	31	29	26	215
1998	14	21	31	30	31	31	30	26	214
1999	18	18	30	30	31	31	30	27	215
2000	18	26	31	30	31	31	30	24	221
2001	15	26	30	30	31	31	30	29	222
2002	17	27	31	30	31	31	30	24	221
2003	16	26	30	30	31	31	30	29	223
2004	22	20	30	30	31	31	30	29	223
2005	9	27	28	30	31	31	30	27	213
Average	16	24	30	30	31	31	30	27	219
Adequate Soil Moisture at 10 cm (SM1>0.21)									
1990	31	30	17	0	21	31	30	31	191
1991	31	12	10	26	31	31	30	18	189
1992	31	30	31	30	6	8	30	8	174
1993	31	2	0	10	20	24	0	14	101
1994	4	0	21	12	4	24	24	17	106
1995	19	4	2	7	12	29	23	4	100
1996	0	0	0	16	31	31	30	21	129
1997	23	23	31	26	0	31	24	11	169
1998	31	28	0	0	23	31	30	31	174
1999	31	7	9	18	11	11	5	0	92
2000	8	7	0	6	9	9	0	22	61
2001	31	7	13	0	4	21	11	0	87
2002	31	7	0	0	19	11	20	18	106
2003	31	13	2	0	0	0	12	15	73
2004	31	30	7	4	9	17	3	26	127
2005	31	30	5	10	4	22	2	31	135
Average	25	14	9	10	13	21	17	17	126
Adequate Air Temperature and Soil Moisture (10 cm)									
1990	17	30	17	0	21	31	30	30	176
1991	12	12	10	26	31	31	27	18	167
1992	17	27	29	30	6	8	30	8	155
1993	13	1	0	10	20	24	0	7	75
1994	3	0	20	12	4	24	24	14	101
1995	11	3	2	7	12	29	21	4	89
1996	0	0	0	16	31	31	30	19	127
1997	18	13	30	26	0	31	23	11	152
1998	14	20	0	0	23	31	30	26	144
1999	18	7	9	18	11	11	5	0	79
2000	7	4	0	6	9	9	0	19	54
2001	15	7	13	0	4	21	11	0	71
2002	17	5	0	0	19	11	20	15	87
2003	16	10	2	0	0	0	12	15	55
2004	22	20	6	4	9	17	3	24	105
2005	9	27	4	10	4	22	2	27	105
Average	13	12	9	10	13	21	17	15	109

Table 7. Number of days with adequate air temperature and soil moisture at 10 cm at the Oil Well site (1990-2005).

Adequate Air Temperature (>10 degree C)								Oil Well, SM1	
				Month					
Year	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Total**
1990	17	30	31	30	31	31	30	30	230
1991	12	28	31	30	31	31	27	31	221
1992	17	27	29	30	31	31	30	31	226
1993	16	25	30	30	31	31	30	25	218
1994	18	25	30	30	31	31	30	28	223
1995	18	21	30	30	31	31	28	30	219
1996	16	26	31	30	31	31	30	23	218
1997	23	17	30	30	31	31	29	26	217
1998	14	21	31	30	31	31	30	25	213
1999	18	19	30	30	31	31	30	27	216
2000	17	25	31	30	31	31	30	24	219
2001	15	25	30	30	31	31	30	29	221
2002	19	27	31	30	31	31	30	23	222
2003	15	26	30	30	31	31	30	29	222
2004	22	20	30	30	31	31	30	29	223
2005	12	27	28	30	31	31	30	27	216
Average	17	24	30	30	31	31	30	27	220
Adequate Soil Moisture at 10 cm (SM1>0.21)									
1990	31	30	16	0	21	31	30	28	187
1991	31	25	10	26	31	31	30	19	203
1992	31	30	31	30	24	31	30	10	217
1993	31	26	10	10	21	26	3	14	141
1994	31	16	21	11	4	24	23	17	147
1995	31	17	2	2	9	20	23	1	105
1996	0	0	0	16	31	31	30	31	139
1997	31	30	29	19	0	28	21	3	161
1998	31	30	31	8	26	25	15	27	193
1999	31	30	18	11	12	9	0	0	111
2000	7	1	0	1	10	6	0	14	39
2001	31	28	12	0	2	25	7	0	105
2002	31	15	0	0	14	12	19	7	98
2003	31	16	0	0	0	0	19	8	74
2004	31	30	9	4	24	20	0	26	144
2005	31	30	14	9	10	22	2	31	149
Average	28	22	13	9	15	21	16	15	138
Adequate Air Temperature and Soil Moisture (10 cm)									
1990	17	30	16	0	21	31	30	27	172
1991	12	24	10	26	31	31	27	19	180
1992	17	27	29	30	24	31	30	10	198
1993	16	21	10	10	21	26	3	8	115
1994	18	13	21	11	4	24	23	15	129
1995	18	12	2	2	9	20	21	1	85
1996	0	0	0	16	31	31	30	23	131
1997	23	17	29	19	0	28	20	3	139
1998	14	21	31	8	26	25	15	23	163
1999	18	19	17	11	12	9	0	0	86
2000	7	0	0	1	10	6	0	11	35
2001	15	23	12	0	2	25	7	0	84
2002	19	13	0	0	14	12	19	4	81
2003	15	13	0	0	0	0	19	8	55
2004	22	20	8	4	24	20	0	24	122
2005	12	27	11	9	10	22	2	27	120
Average	15	18	12	9	15	21	15	13	118

Table 8. Number of days with adequate air temperature and soil moisture between 10 cm and 30 cm at the South House site (1990-2005).

Adequate Air Temperature (>10 degree C)									South House, SM2
				Month					
Year	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Total**
1990	17	30	31	30	31	31	30	30	230
1991	12	28	31	30	31	31	27	31	221
1992	17	27	29	30	31	31	30	31	226
1993	13	24	30	30	31	31	30	24	213
1994	17	24	29	30	31	31	30	26	218
1995	16	18	30	30	31	31	28	30	214
1996	16	25	31	30	31	31	30	23	217
1997	22	16	30	30	31	31	29	26	215
1998	14	21	31	30	31	31	30	26	214
1999	18	18	30	30	31	31	30	27	215
2000	18	26	31	30	31	31	30	24	221
2001	15	26	30	30	31	31	30	29	222
2002	17	27	31	30	31	31	30	24	221
2003	16	26	30	30	31	31	30	29	223
2004	22	20	30	30	31	31	30	29	223
2005	9	27	28	30	31	31	30	27	213
Average	16	24	30	30	31	31	30	27	219
Adequate Soil Moisture between 10 cm and 30 cm (SM2>0.38)									
1990	31	30	17	0	9	31	23	31	172
1991	31	16	10	9	31	31	30	16	174
1992	31	30	31	26	0	0	22	2	142
1993	31	21	0	4	8	0	0	0	64
1994	31	8	21	8	0	17	14	17	116
1995	31	28	2	1	0	21	23	0	106
1996	0	0	0	11	28	31	28	23	121
1997	31	30	31	19	0	31	23	15	180
1998	31	30	13	0	18	31	30	31	184
1999	31	20	9	12	7	2	0	0	81
2000	0	8	0	0	1	0	0	14	23
2001	31	26	15	0	2	19	11	0	104
2002	0	0	0	0	0	0	19	4	23
2003	0	0	0	0	0	0	0	0	0
2004	0	27	4	0	0	0	0	3	34
2005	31	21	4	2	0	0	0	0	58
Average	21	18	10	6	7	13	14	10	99
Adequate Air Temperature and Soil Moisture between 10 cm and 30 cm									
1990	17	30	17	0	9	31	23	30	157
1991	12	15	10	9	31	31	27	16	151
1992	17	27	29	26	0	0	22	2	123
1993	13	15	0	4	8	0	0	0	40
1994	17	7	20	8	0	17	14	14	97
1995	16	16	2	1	0	21	21	0	77
1996	0	0	0	11	28	31	28	18	116
1997	22	16	30	19	0	31	22	12	152
1998	14	21	13	0	18	31	30	26	153
1999	18	12	9	12	7	2	0	0	60
2000	0	5	0	0	1	0	0	11	17
2001	15	22	15	0	2	19	11	0	84
2002	0	0	0	0	0	0	19	4	23
2003	0	0	0	0	0	0	0	0	0
2004	0	18	3	0	0	0	0	3	24
2005	9	19	4	2	0	0	0	0	34
Average	11	14	10	6	7	13	14	9	82

Table 9. Number of days with adequate air temperature and soil moisture between 10 cm and 30 cm at the Oil Well site (1990-2005).

Adequate Air Temperature (>10 degree C)								Oil Well, SM2	
	Month								
Year	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Total**
1990	17	30	31	30	31	31	30	30	230
1991	12	28	31	30	31	31	27	31	221
1992	17	27	29	30	31	31	30	31	226
1993	16	25	30	30	31	31	30	25	218
1994	18	25	30	30	31	31	30	28	223
1995	18	21	30	30	31	31	28	30	219
1996	16	26	31	30	31	31	30	23	218
1997	23	17	30	30	31	31	29	26	217
1998	14	21	31	30	31	31	30	25	213
1999	18	19	30	30	31	31	30	27	216
2000	17	25	31	30	31	31	30	24	219
2001	15	25	30	30	31	31	30	29	221
2002	19	27	31	30	31	31	30	23	222
2003	15	26	30	30	31	31	30	29	222
2004	22	20	30	30	31	31	30	29	223
2005	12	27	28	30	31	31	30	27	216
Average	17	24	30	30	31	31	30	27	220
Adequate Soil Moisture between 10 cm and 30 cm (SM2>0.38)									
1990	31	30	15	0	14	31	24	29	174
1991	31	14	10	11	31	31	30	14	172
1992	31	30	31	30	21	31	29	6	209
1993	31	21	0	10	15	17	0	12	106
1994	31	4	21	8	0	22	19	17	122
1995	27	14	0	0	4	16	11	0	72
1996	0	0	0	13	30	31	29	28	131
1997	31	25	24	14	0	27	21	3	145
1998	31	30	26	0	22	23	4	25	161
1999	29	5	6	4	8	2	0	0	54
2000	0	0	0	0	2	0	0	8	10
2001	31	25	8	0	0	22	0	0	86
2002	0	0	0	0	12	6	8	0	26
2003	0	0	0	0	0	0	14	0	14
2004	0	27	0	4	10	3	0	23	67
2005	31	22	4	6	4	9	0	0	76
Average	21	15	9	6	11	17	12	10	102
Adequate Air Temperature and Soil Moisture between 10 cm and 30 cm									
1990	17	30	15	0	14	31	24	28	159
1991	12	13	10	11	31	31	27	14	149
1992	17	27	29	30	21	31	29	6	190
1993	16	16	0	10	15	17	0	7	81
1994	18	4	21	8	0	22	19	15	107
1995	18	10	0	0	4	16	11	0	59
1996	0	0	0	13	30	31	29	21	124
1997	23	14	24	14	0	27	20	3	125
1998	14	21	26	0	22	23	4	21	131
1999	16	5	6	4	8	2	0	0	41
2000	0	0	0	0	2	0	0	5	7
2001	15	20	8	0	0	22	0	0	65
2002	0	0	0	0	12	6	8	0	26
2003	0	0	0	0	0	0	14	0	14
2004	0	18	0	4	10	3	0	22	57
2005	12	20	4	6	4	9	0	0	55
Average	11	12	9	6	11	17	12	9	87

level of 38% at the South House site (Table 8). The day count was similarly low at the Oil Well site with 14 days of adequate moisture measured during September 2003 (Table 9). The early years of 1990 through 1992 had the most days with desirable growing conditions with about 170 to 180 days of adequate soil moisture and temperature using probe 1 (Tables 6 and 7).

Notice that air temperature greater than 10^{o}C was not a limiting factor relative to soil moisture when defining joint conditions for temperature and soil moisture levels for most of the months. Air temperature was consistently adequate for grass growth in about 219 days of the year. During March, temperature usually was the limiting factor. Soil moisture was high in March with 31 days of adequate moisture in many of the years, but at this time soil temperature was more limiting.

The number of days with favorable moisture and temperature over the March through October growing season had a significant influence on grass yield as would be expected. The results of grass yield regressions are shown in Table 10 (parameters are defined in equations 6 and 7). Parameter A was not found to be statistically significant in any of the models and was excluded. Shifts in the lower asymptote depended on soil moisture conditions. At the extreme, when there were few, if any, days with adequate soil moisture, as was the case during 1993 and 2000, the lower asymptote had minimal adjustment and the regression line was a straight line near the estimate for H in the model. This is evident in the graphs presented in Appendix C where observed snakeweed and grass biomass are plotted against the amount of snakeweed by year.

Table 10. Regressions for estimating grass yield using days with adequate soil moisture and air temperature.

	MODEL 1		MODEL 2	
Parameter	**Parameter Estimate**	**Standard Error**	**Parameter Estimate**	**Standard Error**
H	118.933	43.666*	411.581	28.808**
H_P	5.252	0.393**	3.506	0.335**
A_P	-3.212	0.615**	-3.774	0.826**
B	0.007	0.005	0.006	0.005
M	2.463	2.293	1.861	1.671
R^2		= 0.34		= 0.25
n		= 409		= 409
Mean of dependent variable		= 633		= 633
Root mean squared error		= 300		= 319

Note: Single and double asterisks (*) denote coefficients are statistically different from zero at 1% and 0.01% levels, respectively. The R^2 was computed as the squared coefficient of correlation between the actual and predicted values of the dependent variable.

The marginal change in grass biomass from an added day of desirable soil moisture and temperature (growing day) is different depending on the amount of snakeweed present. If there is no snakeweed the marginal shift in the upper asymptote is measured by H_P, suggesting 5.25 kg/ha of grass is added by another favorable growing day (Model 1). Model 2 suggests this shift to be 3.51 kg/ha using probe 2.

If a heavy infestation of snakeweed is present the marginal change in grass production from an added growing day is measured by H_P+A_P, which for Model 1 is 2.04 and in Model 2 it is -0.74. Based on a Wald test, H_P+A_P was statistically different from zero for Model 1 (p=0.002) but not for Model 2 (p=0.74). Similar to the findings for big sagebrush (*Artemisia tridentata*) by McDaniel et al. (2005), the lower asymptote is relatively fixed regardless of moisture conditions and it is only areas relatively free of snakeweed that respond favorably to improved environmental and weather conditions. Model 2 results indicated the lower asymptote to be fixed at 412 kg/ha ($\hat{H}$) with no significant change from improved moisture conditions. The lower asymptote for Model 1 starts at 119 kg/ha and shifts up by about 2 kg/ha for each added day of adequate soil moisture. The 412 kg/ha level of the lower asymptote in Model 2 remains higher relative to the estimate for Model 1 except during very wet years.

The parameters B and M, which provides curvature for the regression line and adjusts the inflection point, were not found to be significant in any of the models (Tables 10 and 11). Insignificance of these parameters was perhaps because the data did not have much variation in the amount of broom snakeweed except during the early years from 1990 to 1993 (Appendix B) and thus the exact curvature could not be reliably estimated. The estimated snakeweed overstory-understory equations by McDaniel et al (1993) were similar in shape to those estimated here but they were exponentially declining for even minimal levels of snakeweed infestation. The range of grass production in the earlier study is similar to levels on the Corona Ranch, from about 200 kg/ha to 1,400 kg/ha.

Rainfall in the first quarter and second quarter, rainfall during the months of July, August, September, and October, and snakeweed production were used to explain variation in herbage production as Model 3. Numerous other monthly rainfall combinations were considered in alternative models that are not presented. Table 11 shows the results of the regression with rainfall variables.

Table 11. Regression for estimating grass yield by rainfall variables.

Parameter	Parameter Estimate	Standard Error
H	44.220	53.525
H_{P1}	2.152	0.291**
H_{P2}	0.906	0.304*
H_{P3}	2.512	0.221**
A_P	-1.650	0.621*
B	0.004	0.005
M	2.414	3.153
R^2	= 0.32	
n	= 409	
Mean of dependent variable	= 633	
Root mean squared error	= 304	

Note: Single and double asterisks (*) denote coefficients are statistically different from zero at 1% and 0.01% levels, respectively. The R^2 was computed as the squared coefficient of correlation between the actual and predicted values of the dependent variable.

The upper asymptote of the model was estimated to be 44 kg/ha of grass biomass and this level shifts up with additional rainfall. Each millimeter increase in rainfall during the first quarter of the year adds 2.15 kg/ha to the upper asymptote, whereas rainfall in quarter 2 adds 0.91 kg/ha and July through October rainfall adds 2.51 kg/ha. McDaniel et al. (1993) did not find rainfall during quarter 1 to significantly affect grass biomass production and it was a surprising result that rainfall during quarter 1 was estimated to add more to grass yield than did rainfall during quarter 2, based on the statistical test that $H_{P1}=H_{P2}$ ($p<0.0001$) (Model 3, equation 8).

Only rainfall received from July through October was found to shift the lower asymptote of the rainfall overstory-understory model, with H_{P3} estimated to be -1.65 (Table 11). For a particular year, the lower asymptote of the model is estimated as

H+ H_{P1}+ H_{P2}+ H_{P3}+A_P. A test of H_{P3}+A_P=0 was not rejected (p=0.18), suggesting no significant change in the lower asymptote from added rainfall during what is generally considered to be an important growing period for warm season grasses, July through October. The lower asymptote was estimated to shift up with rainfall received early in the year.

Model 1, using the 10 cm depth soil moisture probe 1, had the highest R^2 value at 0.34. This was followed by Model 3 (rainfall) with an R^2 of 0.32. The mean square error ranged from 300 kg/ha for model 1 to 319 for model 2.

Grass yield predicted by Model 1 increases at a constant rate with the number of growing days calculated with soil moisture at 10 cm. Figure 12 shows the number of growing days versus predicted grass yield for three different snakeweed levels; 0

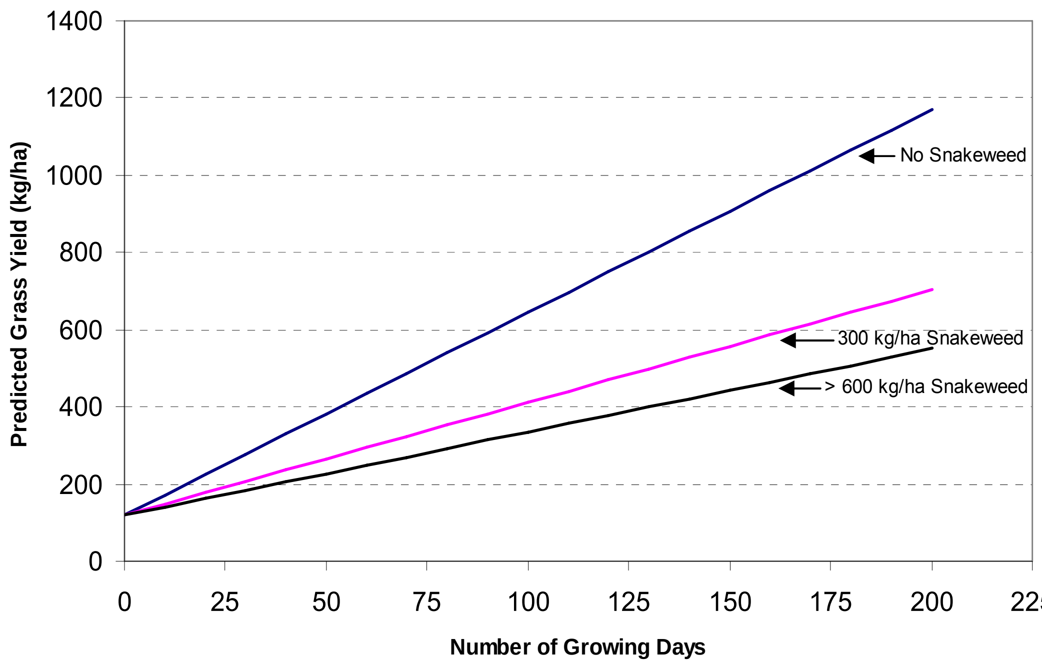


Figure 12. Number of growing days versus predicted grass yield.

kg/ha, 300 kg/ha, and greater than 600 kg/ha. A maximum of 200 growing days was considered to be the likely upper bound. The slope of the curve, which represents the rate at which grass yield increases as number of growing days increases, is lower for higher levels of snakeweed. This shows the effect of snakeweed in suppressing grass production. Site potential is about 1,200 kg/ha.

The graphs of predicted versus actual grass production in Appendix C show that in some years the regression models explained grass production quite well, and for other years they did not. The curvature of the lines, relative to the amount of broom snakeweed, appears to be consistent. Shifts in the location of the curve, and the difference between the upper and lower asymptotes of the curves, is determined by the weather-related variables included in the various models. Obviously, weather variables included in the models did not totally explain the year-to-year variation in grass yield. Other environmental factors were apparently important with attempts to identify and include them in the equations being unsuccessful. Many other variables were considered including soil temperature, air temperature, and relative humidity but other logical statistically significant variables could not be identified.

In some of the years the regression models over predicted grass biomass and in others they under-predicted, though the shape of the curves appeared very consistent with the data in the Appendix C plots. Consider 1990-91 at the Oil Well site (Figures C2 and C4) as an example. Predicted values in these years were consistently 200 kg/ha to much. It is certainly possible that soil moisture and the corresponding number of days with adequate soil moisture were over-predicted for these years.

Economic Value of Water

As noted earlier (Page 39) only predicted values of lagged soil moisture were used and lagged values were not replaced with actual recorded values when estimating how soil moisture would likely change with additional rainfall. This slightly altered the predicted level of soil moisture and correspondingly the day count during the 2003 and 2004 period considered when valuing water. As shown in Table 12, the day count for the predicted series was 5 days less in 2003 and 23 days more in 2004 using predicted values.

The estimated forage response from additional rainfall events varied depending upon the amount of rainfall, timing of rainfall events during the year, the soil moisture conditions at the time of storm, and the assumed level of snakeweed infestation. Table 13 summarizes the changes in forage production resulting from different rainfall events during the years 2003 and 2004 and the corresponding

Table 12. Predicted number of days with adequate air temperature and soil moisture at 10 cm at the South House site (2003-2004) using lagged actual values versus lagged predicted values of soil moisture.

Adequate Air Temperature and Soil Moisture (10 cm)										
		Month								
Year		**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Total**
2003	Using actual values	16	10	2	0	0	0	12	15	55
	Using predicted values	16	0	5	0	0	19	0	10	50
2004	Using actual values	22	20	6	4	9	17	3	24	105
	Using predicted values	12	18	5	4	15	29	16	24	123

Note: Tables 6, 7, 8, and 9 give day counts using lagged actual values for different years and alternative sites.

Table 13. Forage response from rainfall events and value of rainfall.

Date	Δ Rain (mm)	Δ Number of Growing Days	No Snakeweed Δ Grass Yield (kg/ha)	No Snakeweed Value ($) of Δ Grass Yield	300 kg/ha Snakeweed Δ Grass Yield (kg/ha)	300 kg/ha Snakeweed Value ($) of Δ Grass Yield
02/01/03	6.4	0	0	0	0	0
	13.0	0	0	0	0	0
	25.4	0	0	0	0	0
04/01/03	6.4	4	21.0	0.55	11.7	0.30
	13.0	8	42.0	1.09	23.4	0.61
	25.4	16	84.0	2.18	46.8	1.22
05/01/03	6.4	0	0	0	0	0
	13.0	1	5.2	0.14	2.9	0.08
	25.4	7	36.8	0.96	20.5	0.53
07/01/03	6.4	0	0	0	0	0
	13.0	0	0	0	0	0
	25.4	3	15.8	0.41	8.8	0.23
02/01/04	6.4	1	5.3	0.14	2.9	0.08
	13.0	3	15.8	0.41	8.8	0.23
	25.4	4	21.0	0.55	11.7	0.30
04/01/04	6.4	0	0	0	0	0
	13.0	1	5.2	0.14	2.9	0.08
	25.4	1	5.2	0.14	2.9	0.08
05/01/04	6.4	1	5.2	0.14	2.9	0.08
	13.0	2	10.5	0.27	5.8	0.15
	25.4	4	21.0	0.55	11.7	0.30
07/01/04	6.4	1	5.2	0.14	2.9	0.08
	13.0	1	5.2	0.14	2.9	0.08
	25.4	2	10.5	0.27	5.8	0.15

economic value of the rainfall event when grass yield was valued at 2.6 ¢/kg.

As modeled, a rainfall event increases grass production by increasing the number of growing days in the year. Figure 13 shows the estimated effect of a 25.4 mm (1 in) rainfall on April 1, 2003 on soil moisture. The enclosed area of the soil moisture curve in the upper graph is shown in an enlarged view in the lower graph where the dashed curve represents the shift in soil moisture resulting from the rainfall event. The shaded area in the lower graph highlights the added period when SM1 would be pushed above the critical 0.21 level, in this case for 19 additional days.

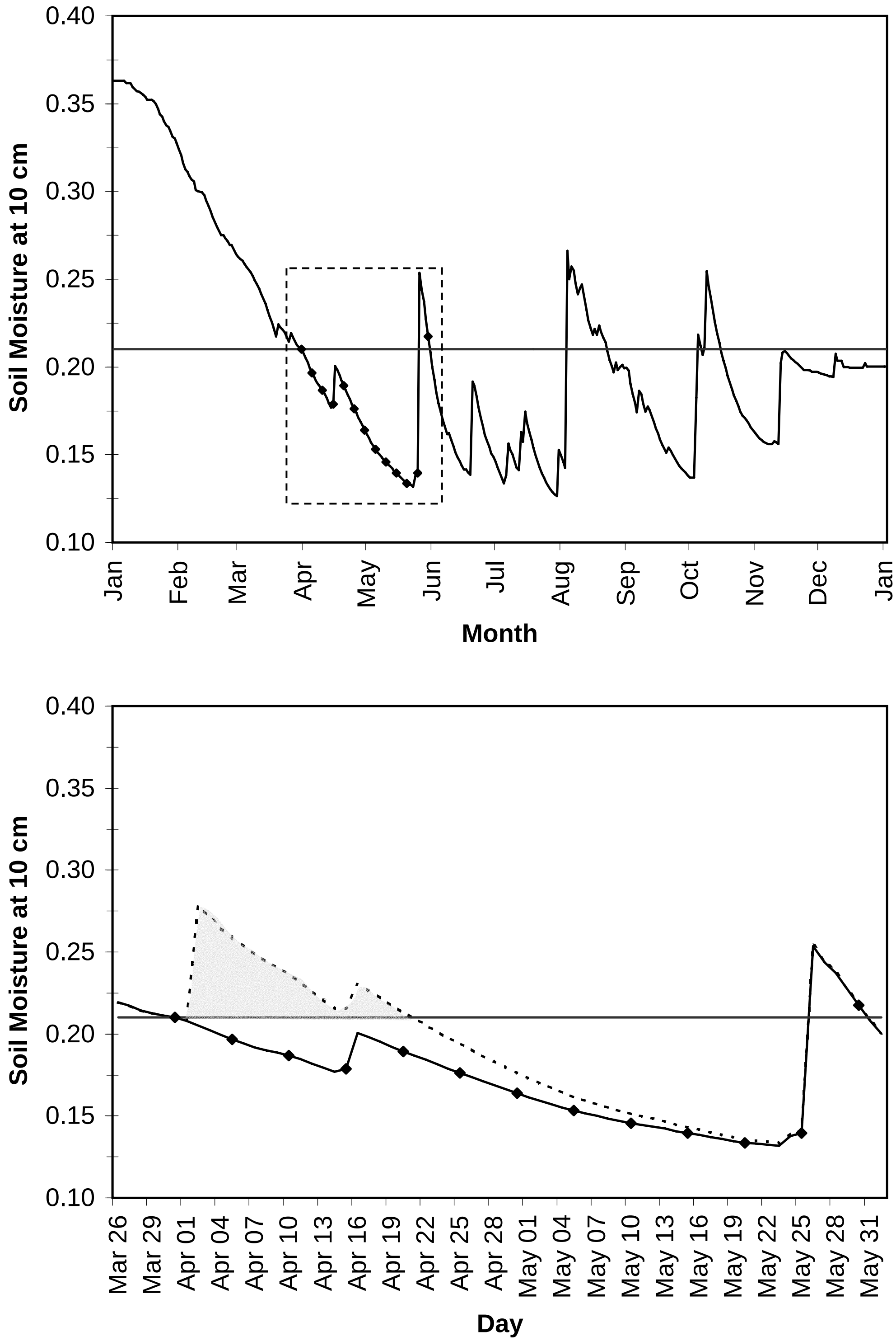


Figure 13. Estimated soil moisture (at 10 cm) in 2003 and the result of a 25.4 mm rainfall event on April 1.

Three of those days did not have adequate temperature and so the net change was 16 days (Table 13). These 16 added days would grow 84 kg/ha of additional grass if there were no snakeweed present for an added economic value of $2.18/ha. The presence of snakeweed had a significant negative effect on the marginal increase of grass yield resulting from rainfall. The forage benefit would be nearly half as much (46.8 kg/ha) if snakeweed production were 300 kg/ha.

As shown in Figure 13, the upward movement of soil moisture continues but diminishes daily until the next storm is realized on May 25. The benefit of a storm obviously depends on its timing and how dry conditions have been. Equal amounts of rainfall had different levels of influence on increasing the number of growing days and thus forage yield even within the same year depending on existing soil moisture conditions. This is especially evident when considering the relatively wet year of 2004. As shown in Figure 14, only storms from about mid-May to mid-June had the potential to substantially add growing days during this year.

Soil moisture (at 10 cm) in February 2003 was always above the critical minimum level (Figure 13), although 2003 was dry in general. Additional rainfall events on February 1, 2003 increased absolute soil moisture levels, but did not add growing days (Table 13). During 2004, soil moisture was generally below the critical minimum level until it rained about 94 mm (3.7 in) during the first week of April. Thus, rainfall events on February 1, 2004 had the potential to raise soil moisture above the critical minimum and they did. Rainfall amounts of 6.4 mm, 13 mm, and

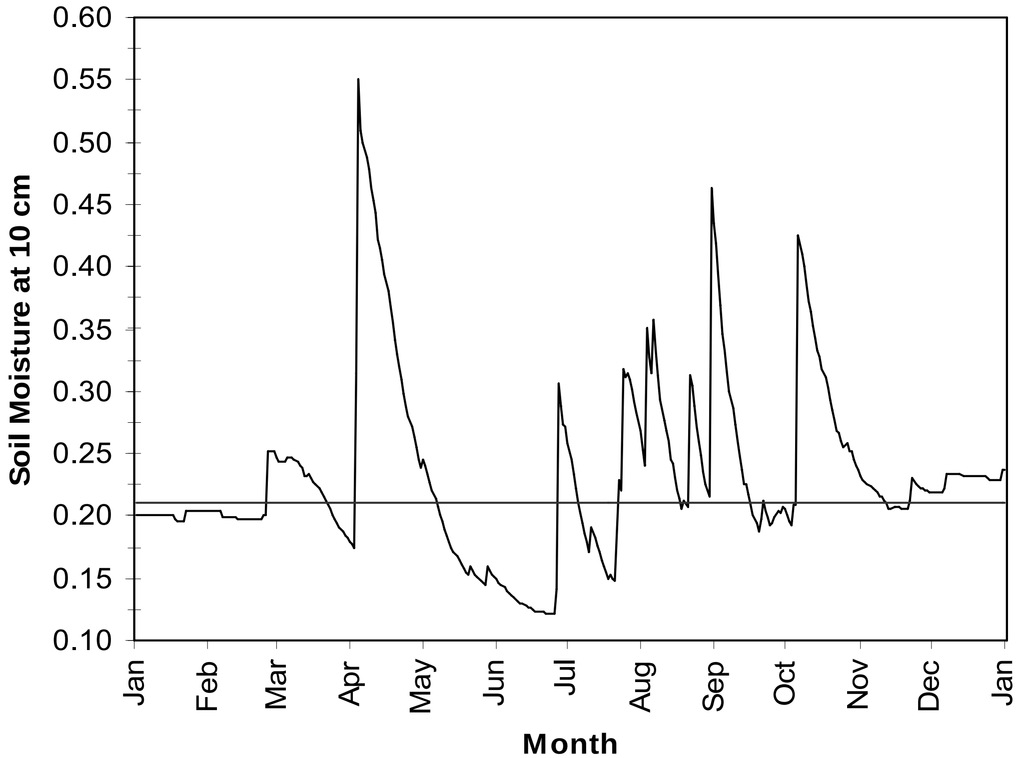


Figure 14. Estimated soil moisture (at 10 cm) in 2004.

25.4 on February 1, 2004 added 1, 3, and 4 growing days, respectively, during 2004. This resulted in increased grass production of an estimated by 5.3, 15.8, and 21 kg/ha with no snakeweed present.

The 170 to 180 growing days estimated for 1990-1992 (Tables 7 and 8) certainly has the potential to have been over estimated given that soil moisture was not recorded on-site over these early years, and with clear overestimation of grass yield during 1990-1991 (Appendix C). The 198 growing days estimated for the Oil Well site during 1992 likely reflects the upper bound on growing days for the Corona Ranch. This value includes nearly every day of the month from April to September

(Table 8). The corresponding 1992 estimated 1,159 kg/ha of grass production with no snakeweed at the Oil Well site is then near the productive potential of the site (Figure 12).

A higher level of rainfall does not always produce more forage. One must consider current soil moisture conditions, timing of rainfall events, and the seasonality of soil moisture decline. These factors are not considered by the rainfall model (Model 3). The estimated change in grass production from the April 1, 2003 25.4 mm storm is estimated to be 23 kg/ha (0.91 kg/ha $\times$ 2.54) using the rainfall model (Model 3). If the same storm occurred in February the estimated marginal increase in grass production would be 55 kg/ha (2.15 kg/ha $\times$ 25.4). The marginal increase would be the same for all levels of snakeweed. The estimated marginal change would also be the same for all years because the rainfall model does not consider soil moisture conditions. This is an obvious limitation of using rainfall to predict grass biomass production.

Consider again the 84 kg/ha of added forage production estimated using the soil moisture model from a 25.4 mm rainfall event on April 1, 2003. During 2003 grass biomass production averaged 281 kg/ha on the South House site with very little snakeweed present (Figure 3). The added 84 kg/ha of grass production from the assumed April 1 rainstorm of 25.4 mm represents a 30% increase in grass production for this dry year. The Corona Ranch has about 11,381 ha (28,112 acres) of total rangeland of which 6,175 ha (15,250 acres) is designated to be blue grama grassland (McDaniel 2002). The assumed single 25.4 mm rainstorm is then estimated to produce 518,700 kg of added grass on the relatively productive blue grama grassland areas of the ranch. This is enough forage to carry 119 head for the year (1,429 AUM) for an estimated economic value of $13,462 when valued at 2.6 ¢/kg. The less productive pinyon-juniper rangeland areas would also receive an expected boost in forage production such that the estimated economic value of the rainstorm reflects a minimum level. This is further true if the storm eliminated the need for drought-related herd reductions.

DISCUSSION

Earlier studies have estimated grass yield directly from precipitation levels. But estimating grass production from rainfall has some serious limitations. Grass growth does not depend only on the amount of rainfall; it also depends on other factors like air temperature, soil temperature, and relative humidity. Rainfall as an explanatory variable in predicting forage production does not measure the effects of these factors and also fails to recognize the existing water available in the soil. If the soil is already saturated a rainfall event would add very little to grass production. The number of days when soil moisture measured at 10 cm was above some critical level was determined to provide a better measure of moisture conditions when predicting forage production. This was especially true conceptually because soil moisture measurements consider timing of rainfall events as well as existing soil moisture conditions.

Several data problems were encountered that influenced the statistical results and how the results can be interpreted. Soil moisture data were not always recorded and the soil moisture probes did not always work error free. This meant regression equations had to be developed to predict and fill in the data gaps. The quantification of the relationships between measured soil moisture, rainfall, and other environmental variables was also required for making predictions about how soil moisture and the corresponding grass biomass production would change if additional rainstorms occurred in selected years. Improvements can likely be made to the soil moisture equations as they now tend to under-predict the daily change in soil moisture when soil moisture the previous day is at a low level. This is not perceived to be a major problem, however, because computation of growing days requires only an estimate of whether soil moisture is at or below some critical level, and absolute level of the measurement is less important.

There was a systematic difference between the volumetric soil moisture content measurements taken by the probes at the two study sites suggesting a probe calibration error. Additional steps need to be made to calibrate the soil moisture probes so that they accurately measure volumetric soil moisture. This may suggest a re-scaling and re-estimation of some of the results presented in this thesis.

Grass yield data was collected only once during the year in November. If this data was collected two or three times during the year the predictive power of grass yield models might be improved and the seasonal pattern of grass production could be quantified and related to seasonal soil moisture conditions. This is a potential area for future research. Lack of variation in snakeweed production across years limited the reliability of the estimated overstory-understory relationships for broom snakeweed, though the results were consistent with those McDaniel et al. (1993).

Though data limitations were encountered, the data used in this study is unique. Grass yield data was consistently recorded over 16 years. Soil moisture probes recorded soil moisture over nearly 6 of those years, and rain gauges at or adjacent to the study sites recorded hourly rainfall levels and frequency over the total study period. Continued monitoring of soil moisture at the study sites, and on other

New Mexico ranches, can potentially improve decisions about drought management, desired rangeland stocking rates, and the expected frequency of both drought and above-average soil moisture conditions. The explanatory weather related variable used in the soil moisture grass yield models (number of growing days encountered over the year) suggests, for example, that there will not be some rainfall event that will “catch the ranch up” on forage production. The results indicate about 5 kg/ha of forage will grow for every day that growing conditions exceed the estimated critical levels. If it is July and it has not rained and with low soil moisture a greatly reduced level of total forage production for the year should be expected.

For stocking rate decisions, ranchers need an estimate of how much forage was grown over the year, or preferably how much will grow over the coming year. The grass yield equation can provide this estimate once the number of growing days is determined. This would be useful in the sense that the ranchers will not have to actually go to the field and take grass clippings. Further, at any point during the year they would be able to estimate the amount of grass that has already grown.

The influence of snakeweed in suppressing grass yield on blue grama rangeland was noticeable and interacted to reduce the efficiency of added rainfall in increasing grass yields. Presence of 300 kg/ha of snakeweed reduced forage response from rainfall events by nearly fifty percent. This highlights the importance of controlling broom snakeweed and potentially other woody plant species if improved efficiency of water use on rangelands is an important issue.

APPENDICES

APPENDIX A

THE CORONA WEATHER DATABASE: USER MANUAL

The Corona Weather Database currently summarizes weather data collected over 16 years on the NMSU's Corona Range and Livestock Research Center (Corona Ranch). Two long-term snakeweed study sites 'South House' and 'Oil Well' were established on the Corona Ranch in 1990. Weather was monitored starting from July 17, 1990 at South House and from November 9, 1990 at Oil Well by automated weather stations (Campbell Scientific model CR-10 multiport data loggers powered by a solar recharged battery system) recording hourly air temperature, soil temperature (at 10 and 50 cm from the surface), relative humidity, wind speed, wind direction, and rainfall. Monitoring of soil moisture was started in September and October of 2001 at South House and Oil Well, respectively. Soil volumetric water content at 10-cm depth and average soil moisture between 10 cm and 30 cm were recorded using soil moisture probes (CS 615-L, Campbell Scientific Inc.).

All the weather data were downloaded and recorded into separate spreadsheet files over the 16-year study period by Dr. Kirk C. McDaniel and his students. Data are now recorded in a similar way by professional staff stationed at the Corona Ranch. Annual spreadsheet files are maintained on the web server of the Department of Animal and Range Sciences, New Mexico State University.

Corona Ranch personnel record data on various sheets within the annual weather spreadsheet, and tabulate that data by day in addition to the hourly recordings made by the CR-10 recorder. Hourly recordings are recorded in the spreadsheet for a particular site based on the Julian date of the CR-10 recording. The text file from the CR-10 recorder is imported into Excel^{TM}.

The Corona weather Access database stores data in tables with queries used to visualize the data in various ways. This is the standard format used by database programs. Tables included in the Access program are shown in Figure A1 and the important ones for users are described in detail below.

If all goes well and the CR-10 recorder functions properly with no skips in data recordings over the period, hourly data are added to the table called "Summary" in Figure A1. This is the main and most basic table of the database and it contains 20 data columns as described below. This table contains hourly data. Variables included in the table are:

1. SITE: Code name of site (101 for South House and 201 for Oil Well)

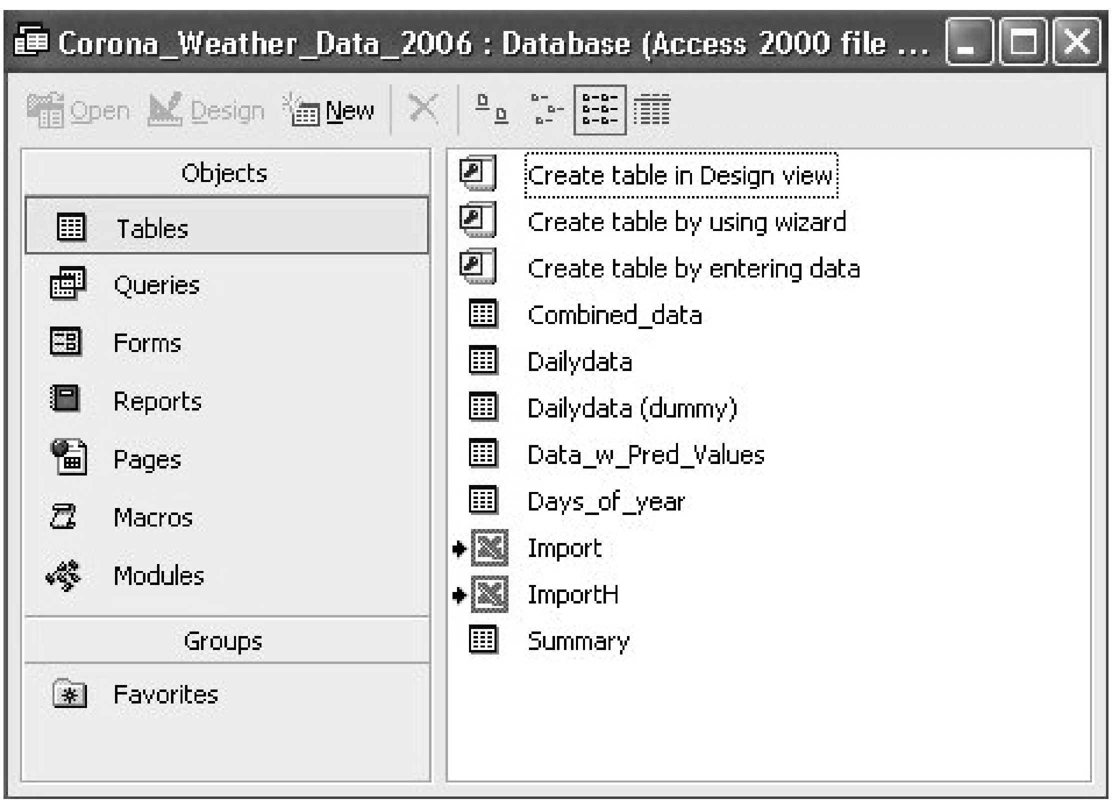


Figure A1. Tables in the Access database.

2. SITENAME: Name of site (SH South House and OW for Oil Well)
3. YEAR: Four digit year number (e.g. 1990)
4. MONTH: Serial number for the months of a year (e.g. 6 for June)
5. WEEK: Serial number for the week of the year (e.g. 45 for 11/1/2005)
6. DAY: Serial number for the day of the year (e.g. 305 for 11/1/2005)
7. HOUR: Serial number for the hour of the day (e.g. 100 for 1:00 AM and 2400 for 12 AM)
8. DATE/TIME: Date and time of a particular day (e.g. 10/30/2005 8:00 PM)
9. ATEMP: Air temperature (^{o}C)
10. STEMP1: Soil temperature (^{o}C) at 10 cm
11. STEMP2: Soil temperature (^{o}C) at 50 cm
12. RH: Relative humidity
13. WS: Wind speed (meter/second)
14. WD: Wind direction (degrees on the compass)
15. VOLT: Voltage on system
16. RAIN: Rainfall (mm)
17. Extra1: This column actually contains nothing. Users should ignore this column.
18. Extra2: This column actually contains nothing. Users should ignore this column.
19. SMOIS1: Soil moisture at 10 cm
20. SMOIS2: Average soil moisture between 10 cm and 30 cm

For the convenience of new users a welcome screen with buttons to open different tables and queries and to add new hourly or daily data has been built in the MS Access database (Figure 2). From this screen a user can browse various parts of the database with a mouse click. Data is most easily seen from the Welcome screen. The user can also view the data by opening the following queries:

- Hourly data – Open “Query_Combined_Daily”
- Daily data – Open “Query_All_Data”
- Monthly data – Open “Monthly Summary Query”

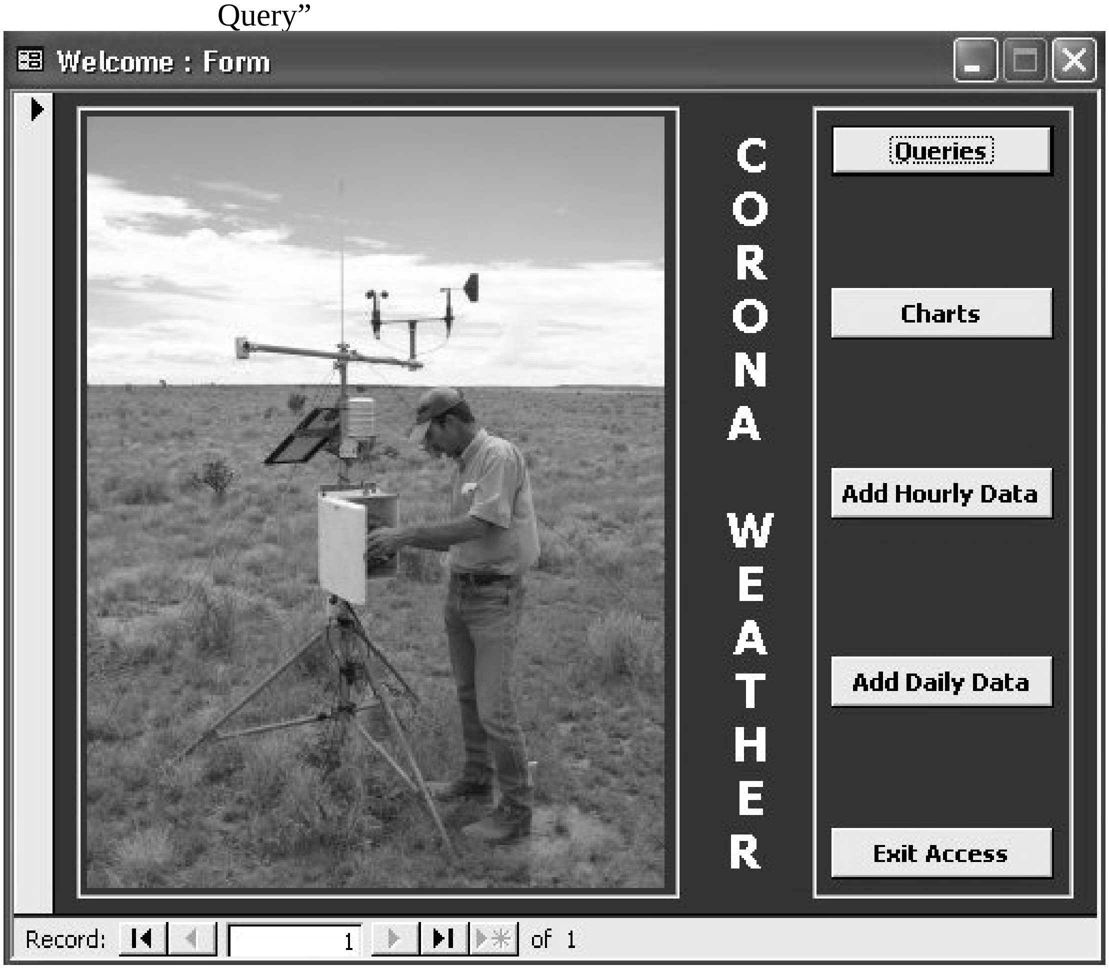


Figure A2. Welcome screen in the Access database.

The knowledgeable user can open one of the three queries in design view and set criteria to display subsets of the data. Be sure and remove the criteria before exiting the program.

A description of the menu on the Welcome screen follows.

- Queries: Single clicking on this button opens another menu containing four buttons and these buttons open alternative queries to view either hourly, daily, or monthly data.
  i. Hourly Data. The query called Query_All_Data is opened.
  ii. Daily Data. The query called Query_Combined_Daily is opened. Note that if the most recent data is not displayed you may need to update the daily data by using the “Add Daily Data” button on the Welcome screen.
  iii. Monthly Data. Opens a query that displays monthly rainfall totals and soil moisture averages for the month.
  iv. Exit. Go back to the Welcome screen.
- Charts: Single clicking on this button opens another menu containing links for different charts.
- Add Hourly Data: Single click on this button and follow the instructions carefully to add new hourly data to the database. The detailed instructions about this can be found below under “Adding new hourly data to the Weather Database”.

- Add Daily Data: Single click on this button to update the table containing daily data in the database. The detailed instructions on this can be found below under “Replacing missing Data”.
- Exit Access: Exits MS Access.

Adding New Hourly Data to the Weather Database

1. Open Excel and select the File/Open option.
2. Navigate to where the CR-10 data file is located and select “All Files” in the “Files of Type” section.
3. Choose the “Delimited” option in the “Text Import Wizard” and using “Comma” as the separator retrieve the data from the data logger file into Excel.
4. Delete columns M and N as they are not needed.
5. Click on the header of column B and insert a blank column. If column A is “101” add “SH” and if column A is “201” add “OW” to the corresponding cells in this new column. You are adding a column with the abbreviations for the research sites.
6. Column C is now YEAR. Click on Column D and insert two blank columns.
7. Column H is now ATEMP. Click on column H and insert a blank column. In cell H1 type the formula "=DATE (C1, 1, F1) +TIME (G1/100, 0, 0)" and

copy it down. Format this column with a date and time format (e.g., 3/14/01 1:30 PM). Verify that the correct date and time are displayed.

8. In cell D1 type the formula "=MONTH (H1)" and copy it down.
9. In cell E1 type the formula "=WEEKNUM (H1,2)" and copy it down. If this formula does not work go to Add-Ins under the Tools menu and select "Analysis ToolPak".
10. At column Q, which should now be SMOIS1, insert two blank columns. The spreadsheet should now include data through column T and be organized into 20 columns of data as described earlier. Now paste the data from this temporary Excel file to the spreadsheet called "Add hourly data to this table.xls". This spreadsheet has the required headings and Access macros use this file to import from. The file is available on the Animal and Range Science server.
11. In "Add hourly data to this table.xls" delete all the data (except the column headings) on the sheet titled "Insert Data Here". From left to right the columns should be SITE, SITENAME, YEAR, MONTH, WEEK, DAY, HOUR, DATE/TIME, ATEMP, STEMP1, STEMP2, RH, WS, WD, VOLT, RAIN, Extra1, Extra2, SMOIS1, and SMOIS2.
12. Paste the data from the temporary spreadsheet file you built with all cells pasted as values. Verify that all columns match and are in the right order.
13. Now, select all of the data including the column headings. In the menu bar go to "Insert", then "Name", and then "Define". A dialog box with caption

"Define Name" will pop up. Write "Import" in the space given just below "Names in workbook" in the dialog box. Then click on "OK" on the right hand side of the dialog box. This provides a named range called "Import" for the data import.

14. Save and close the spreadsheet file.
15. Open the Weather Database called "Corona_Weather_Data_2006.mdb". In the Welcome screen click on "Add Hourly Data" (Figure A2). As you proceed, a message box will pop warning about adding data properly to the Excel file. If you have done the previous two steps properly then click "Next". Read the instructions carefully and click "Continue". Select "ImportH" as was described in the previous menu. Note that the mouse pointer may look busy at this point, but proceed anyway. Click "OK" to refresh the links. Microsoft Access confirms a successful refresh. Click "OK" again on the dialog box that pops up and then click "Close" on the "Linked Table Manager".
16. A macro is executed that transfers the data from the spreadsheet called "Add hourly data here.xls" to the bottom of the Access table called "Summary". A message box will pop up confirming successful transfer. Click on "Ok" in the message box. Open the table called "Summary" and verify the data was imported correctly.
17. To update the daily data tables and queries with the new data click on the "Add daily Data" button on the Welcome screen and follow the directions (detailed later in this manual).

Replacing Missing Data

Recording errors and human error ultimately results in missing data at weather recording stations. When data were missing the following actions were taken in descending order for the years already in the weather database. The same procedures can be taken in the future for replacing missing data.

A. The missing data were replaced for a particular day and/or time from one study site with the corresponding data from the other study site (South House and Oil Well). Soil moisture data were not replaced across sites because the recorders are not calibrated the same.

B. If data were not available from the other study site, the web site "http://weather.nmsu.edu/" was used to gather weather data. This weather station is located at the North Camp Facility on the Corona Ranch and records hourly data. It is a part of the NMSU State Climate Network.

C. When the above two procedures failed, the website "http://www.ncdc.noaa.gov/" was used to collect corresponding data from different weather stations near the Corona ranch including Ramon and Corona 10 SW.

D. Much of the data that were missing during the early part of the study period were replaced with daily data gathered from nearby weather stations by Garrett Timmons (Z:\McDanLAB\Coronaweather\1990-2003 Garrett weather pivot table.xls).

Hourly Data

Hourly data that were replaced from an alternative weather station were identified in the last two columns of the “Summary” table. The replaced records are most easily viewed from the query called “Replaced_Hourly_Data”. By running the query it can be seen that 29,073 hourly records were replaced. Appropriate conversions from English units to metric units were made.

Daily Data

In some cases hourly data were not available and daily weather recordings were used. Daily data were used to define weather variables from September 1989 until October 1990 when the weather stations at the study sites became operational. Nearby NOAA data were primarily used by Garrett Timmons to define weather conditions during these early years of the study. The amount of rainfall was usually the only useful data recorded in the daily data file.

To add daily data to the database, open the Excel file “Add daily data to this table.xls”. The data is stored on Sheet1. Descriptions of variables are given on Sheet2. Data for many of these variables were not available on a daily basis. But the variable names are needed as placeholders and for proper merging with the hourly data once it is tabulated to a daily time step.

It is important that you do not delete any of the existing data from the spreadsheet file. Instead, add new data to the end of appropriate columns. Enter “1” under the column "Count" (column AF) for each entry, indicating that one daily value is being recorded.

Once the data is entered you must redefine the length of range name that will be exported to Access. To do this, select all of the data (old plus new) including the column headings. In the menu bar go to "Insert", then "Name", and then "Define". A dialog box with caption "Define Name" will pop up. Type "Import" in the space given just below where it says "Names in workbook" in the dialog box. Then click "OK" on the right hand side of the dialog box. Save the spreadsheet file.

The next step is to import and link the daily data to the Access database. To do this open the Weather Database (Corona_Weather_Data_2006.mdb). In the Welcome screen click on "Queries" and then click on "Hourly Data". The hourly data query will open. Now, go to "View" in the Access menu bar and click on "Design View". Make sure that no criterion is set for the hourly data query. Close the query and exit back to the Welcome screen.

In the Welcome screen click on "Add Daily Data". Read the instructions carefully and click "Continue". The "Linked Table Manager" will open. Select the check box on the left of "Import". Note that the mouse pointer may look busy at this point, but proceed anyway. Click "OK" to refresh the links. Microsoft Access confirms a successful refresh. Click "OK" again on the dialog box that pops up and then click "Close" on the "Linked Table Manager". This refreshes the interactive link with the daily data table that is stored in Excel. This will execute a macro called "Add Daily Data" that first deletes the existing "Dailydata" and recreates a blank table with the same name and same headings, and then adds to this the imported daily data and tabulations of daily values calculated from the hourly data in the database. Two sources of data are merged; the Excel table called “Import” and the Access query called “Daily_Averages”. Two append queries are executed for this purpose, Append1 and Append2, stored in the “Queries” section of the Access database. A message box will pop up confirming the successful addition of data.

APPENDIX B

GRASS AND SNAKEWEED YIELD FROM 1990 THROUGH 2005

Table B1. Grass and Snakeweed (Gusa) yield (kg/ha) and standard deviation (SD) within selected treatments and plots at the South House Site (1990-2005).

Site Name	SH

Treatment Number	Plot Number	Year	Grass Average (kg)	Grass (SD)	Gusa Average (kg)	Gusa (SD)	Predicted Grass (kg)
0	5	1990	337	141	339	534	831
		1991	178	62	297	467	803
		1992	482	126	217	541	838
		1993	392	120	141	315	467
		1994	264	59	4	11	649
		1995	429	49	0	0	586
		1996	727	147	0	0	786
		1997	759	181	0	0	917
		1998	1,566	125	0	0	875
		1999	631	132	0	0	534
		2000	128	71	0	0	403
		2001	407	229	75	120	455
		2002	982	368	4	13	575
		2003	281	80	0	0	408
		2004	781	233	0	0	670
		2005	609	204	0	0	670
	5 Total		559	383	67	254	654
	14	1990	473	149	290	437	851
		1991	257	138	640	1,036	835
		1992	796	363	501	881	784
		1993	470	155	121	382	489
		1994	358	166	0	0	649
		1995	447	93	0	0	586
		1996	747	196	0	0	786
		1997	832	196	0	0	917
		1998	1,571	265	0	0	875
		1999	881	214	0	0	534
		2000	178	66	0	0	403
		2001	539	206	37	79	471
		2002	651	305	0	0	576
		2003	285	116	0	0	408
		2004	706	275	0	0	670
		2005	884	240	0	0	670
	14 Total		630	386	99	403	657

Continued

Table B1. Grass and Snakeweed (Gusa) yield (kg/ha) and standard deviation (SD) within selected treatments and plots at the South House Site (1990-2005).

Site Name	SH

Treatment Number	Plot Number	Year	Grass Average (kg)	Grass (SD)	Gusa Average (kg)	Gusa (SD)	Predicted Grass (kg)
0	24	1990	356	173	822	1,247	817
		1991	239	78	801	1,409	835
		1992	691	208	635	1,385	785
		1993	406	113	157	347	466
		1994	284	146	21	67	632
		1995	388	104	47	149	560
		1996	903	156	0	0	786
		1997	671	199	0	0	917
		1998	1,711	271	0	0	875
		1999	590	149	98	237	493
		2000	195	58	137	434	385
		2001	426	106	269	852	469
		2002	498	179	0	0	576
		2003	246	66	0	0	408
		2004	513	178	0	0	670
		2005	761	140	66	208	637
	24 Total		555	388	191	674	645
0 Total			581	386	119	478	652
3	4	1990	595	141	0	0	1043
		1991	318	65	0	0	996
		1992	1,101	326	0	0	933
		1993	984	293	0	0	513
		1994	383	123	0	0	649
		1995	712	236	0	0	586
		1996	1,085	221	0	0	786
		1997	847	167	0	0	917
		1998	1,321	279	0	0	875
		1999	786	210	0	0	534
		2000	200	67	0	0	403
		2001	460	170	17	52	483
		2002	1,044	290	0	0	576
		2003	281	80	0	0	408
		2004	767	231	0	0	670
		2005	673	188	0	0	670
	4 Total		722	379	1	13	690

Continued

Table B1. Grass and Snakeweed (Gusa) yield (kg/ha) and standard deviation (SD) within selected treatments and plots at the South House Site (1990-2005).

Site Name	SH

Treatment Number	Plot Number	Year	Grass Average (kg)	Grass (SD)	Gusa Average (kg)	Gusa (SD)	Predicted Grass (kg)
3	11	1990	524	176	0	0	1043
		1991	332	60	0	0	996
		1992	882	298	0	0	933
		1993	911	222	0	0	513
		1994	453	144	0	0	649
		1995	831	197	0	0	586
		1996	1,144	294	0	0	786
		1997	1,004	306	0	0	917
		1998	1,812	292	0	0	875
		1999	926	247	235	743	508
		2000	293	152	196	619	385
		2001	603	218	0	0	492
		2002	685	314	0	0	576
		2003	363	137	0	0	408
		2004	852	241	0	0	670
		2005	1,007	252	0	0	670
	11 Total		789	431	27	241	688
	21	1990	445	195	0	0	1043
		1991	356	63	0	0	996
		1992	1,435	294	0	0	933
		1993	950	184	0	0	513
		1994	474	226	0	0	649
		1995	726	145	0	0	586
		1996	1,210	226	0	0	786
		1997	876	249	0	0	917
		1998	1,791	213	0	0	875
		1999	786	225	0	0	534
		2000	238	80	0	0	403
		2001	376	143	0	0	492
		2002	642	184	17	52	565
		2003	458	213	0	0	408
		2004	687	224	0	0	670
		2005	896	295	98	311	637
	21 Total		772	454	7	79	688
3 Total			761	423	12	147	689

Continued

Table B1. Grass and Snakeweed (Gusa) yield (kg/ha) and standard deviation (SD) within selected treatments and plots at the South House Site (1990-2005).

Site Name	SH

Treatment Number	Plot Number	Year	Grass Average (kg)	Grass (SD)	Gusa Average (kg)	Gusa (SD)	Predicted Grass (kg)
6	7	1991	225	43	3	11	995
		1992	801	258	0	0	933
		1993	779	167	0	0	513
		1994	292	69	0	0	649
		1995	520	110	0	0	586
		1996	883	139	0	0	786
		1997	720	170	0	0	917
		1998	1,591	170	0	0	875
		1999	538	108	0	0	534
		2000	150	62	0	0	403
		2001	194	137	25	65	479
		2002	469	153	8	26	572
		2003	289	108	0	0	408
		2004	583	211	0	0	670
		2005	498	194	39	125	642
	7 Total		569	382	5	37	664
	13	1991	211	45	52	166	946
		1992	629	112	121	383	883
		1993	504	158	48	153	491
		1994	288	126	25	78	629
		1995	502	124	0	0	586
		1996	899	262	0	0	786
		1997	803	129	0	0	917
		1998	1,511	200	0	0	875
		1999	741	158	0	0	534
		2000	143	50	0	0	403
		2001	484	168	0	0	492
		2002	623	362	0	0	576
		2003	315	132	0	0	408
		2004	616	222	0	0	670
		2005	940	214	0	0	670
	13 Total		614	376	16	116	658

Continued

Table B1. Grass and Snakeweed (Gusa) yield (kg/ha) and standard deviation (SD) within selected treatments and plots at the South House Site (1990-2005).

Site Name	SH

Treatment Number	Plot Number	Year	Grass Average (kg)	Grass (SD)	Gusa Average (kg)	Gusa (SD)	Predicted Grass (kg)
6	22	1991	272	58	70	169	923
		1992	1,206	229	96	304	883
		1993	700	157	113	356	489
		1994	313	153	0	0	649
		1995	511	96	0	0	586
		1996	906	202	0	0	786
		1997	783	180	0	0	917
		1998	1,546	162	0	0	875
		1999	636	164	0	0	534
		2000	163	88	0	0	403
		2001	381	102	0	0	492
		2002	570	180	0	0	576
		2003	497	198	0	0	408
		2004	438	128	0	0	670
		2005	661	122	0	0	670
	22 Total		639	383	19	128	657
6 Total			607	381	13	102	660
10	31	1993	514	145	294	431	421
		1994	391	172	110	276	604
		1995	372	148	118	372	558
		1996	901	215	80	254	746
		1997	808	248	20	63	893
		1998	1,016	530	444	911	727
		1999	373	203	2,003	2,928	432
		2000	53	40	402	697	351
		2001	453	240	369	972	440
		2002	1,001	359	21	66	561
		2003	413	102	0	0	408
		2004	753	233	0	0	670
		2005	892	173	190	602	637
	31 Total		611	373	312	1,038	573

Continued

Table B1. Grass and Snakeweed (Gusa) yield (kg/ha) and standard deviation (SD) within selected treatments and plots at the South House Site (1990-2005).

Site Name	SH

Treatment Number	Plot Number	Year	Grass Average (kg)	Grass (SD)	Gusa Average (kg)	Gusa (SD)	Predicted Grass (kg)
10	33	1993	641	213	1,320	1,627	393
		1994	358	106	0	0	649
		1995	244	105	235	745	558
		1996	1,317	388	0	0	786
		1997	1,175	310	30	54	889
		1998	1,626	160	112	244	789
		1999	846	188	681	1,435	483
		2000	108	24	514	1,122	368
		2001	321	128	418	1,037	433
		2002	469	300	0	0	576
		2003	231	105	0	0	408
		2004	663	213	0	0	670
		2005	641	154	0	0	670
	33 Total		665	488	255	824	590
	42	1993	269	168	1,163	548	297
		1994	280	109	411	315	426
		1995	315	106	757	653	365
		1996	854	240	227	283	625
		1997	930	271	85	183	833
		1998	1,391	369	147	236	747
		1999	520	167	583	898	433
		2000	138	80	646	751	316
		2001	225	85	1,297	2,142	417
		2002	551	287	0	0	576
		2003	143	85	210	463	373
		2004	682	176	0	0	670
		2005	661	193	0	0	670
	42 Total		535	402	425	824	519
10 Total			604	426	330	902	561

Continued

Table B1. Grass and Snakeweed (Gusa) yield (kg/ha) and standard deviation (SD) within selected treatments and plots at the South House Site (1990-2005).

Site Name	SH

Treatment Number	Plot Number	Year	Grass Average (kg)	Grass (SD)	Gusa Average (kg)	Gusa (SD)	Predicted Grass (kg)
13	10	1991	164	55	1,417	1,098	621
		1992	458	195	2,347	3,133	586
		1993	313	150	491	882	418
		1994	247	162	0	0	649
		1995	411	53	27	87	567
		1996	805	139	0	0	786
		1997	681	164	50	158	872
		1998	1,516	138	58	183	831
		2000	138	59	0	0	403
		2001	321	74	25	56	480
		2002	627	452	0	0	576
		2003	328	186	0	0	408
		2004	838	396	91	288	637
		2005	526	205	36	114	643
	10 Total		527	401	324	1,108	605
	34	1993	548	218	411	805	443
		1996	1,075	321	0	0	786
		1997	1,004	231	5	16	915
		2000	158	72	0	0	403
		2001	474	220	323	979	463
		2002	737	303	21	66	561
		2004	809	163	0	0	670
	34 Total		687	371	108	488	606
	35	1993	661	217	153	365	468
		1994	412	116	0	0	649
		1995	224	65	0	0	586
		1996	1,145	334	0	0	786
		1997	921	237	10	32	908
		1998	1,541	158	23	52	853
		1999	360	46	108	228	486
		2000	118	50	343	732	368
		2001	651	296	186	453	446
		2002	857	368	0	0	576
		2003	356	106	0	0	408
		2004	965	187	0	0	670
		2005	768	134	0	0	670
	35 Total		691	434	63	275	606

Continued

Table B1. Grass and Snakeweed (Gusa) yield (kg/ha) and standard deviation (SD) within selected treatments and plots at the South House Site (1990-2005).

Site Name	SH

Treatment Number	Plot Number	Year	Grass Average (kg)	Grass (SD)	Gusa Average (kg)	Gusa (SD)	Predicted Grass (kg)
13	40	1991	346	155	402	853	889
		1992	844	296	305	646	833
		1993	676	175	48	153	491
		1994	334	88	0	0	649
		1995	180	77	0	0	586
		1996	836	209	0	0	786
		1997	798	185	0	0	917
		1998	1,356	312	81	256	829
		1999	445	101	0	0	534
		2000	160	36	0	0	403
		2001	284	71	17	52	483
		2002	704	214	25	79	558
		2003	192	69	96	302	390
		2004	503	144	0	0	670
		2005	693	245	0	0	670
	40 Total		557	363	65	308	646
13 Total			602	400	145	667	618
Grand Total			632	408	117	548	638

Note: Treatment and plot numbers are defined in Figure 1.

Table B2. Grass and Snakeweed (Gusa) yield (kg/ha) and standard deviation (SD) within selected treatments and plots at the Oil Well Site (1990-2005).

Site Name	OW

Trt No.	Plot No.	Year	Grass Average (kg)	Grass (SD)	Gusa Average (kg)	Gusa (SD)	Predicted Grass (kg)
0	15	1990	407	66	273	717	917
		1991	431	151	203	502	954
		1992	727	250	50	157	1100
		1993	426	157	161	339	650
		1994	411	193	58	126	739
		1995	502	83	161	309	496
		1996	772	190	71	172	749
		1997	1,058	218	40	110	811
		1998	1,331	294	4	12	974
		1999	726	220	69	217	544
		2000	340	192	0	0	303
		2001	91	45	12	28	556
		2002	302	238	0	0	544
		2003	346	175	0	0	408
		2004	729	347	0	0	760
		2005	1,184	230	0	0	749
	15 Total		611	388	69	264	703
	25	1990	393	67	315	790	913
		1991	421	88	220	502	950
		1992	513	97	62	196	1097
		1993	416	53	201	511	654
		1994	335	65	0	0	796
		1995	557	113	47	149	540
		1996	727	308	36	113	773
		1997	1,072	352	0	0	849
		1998	1,321	224	0	0	975
		1999	1,086	125	0	0	571
		2000	160	88	0	0	303
		2001	61	64	166	524	533
		2002	230	304	62	197	519
		2003	320	218	0	0	408
		2004	1,280	307	0	0	760
		2005	792	326	430	1,361	711
	25 Total		605	434	96	456	709

Continued

Table B2. Grass and Snakeweed (Gusa) yield (kg/ha) and standard deviation (SD) within selected treatments and plots at the Oil Well Site (1990-2005).

Site Name	OW

Trt No.	Plot No.	Year	Grass Average (kg)	Grass (SD)	Gusa Average (kg)	Gusa (SD)	Predicted Grass (kg)
0	34	1990	356	55	427	554	757
		1991	300	55	630	1,020	813
		1992	595	140	1,213	1,930	842
		1993	446	119	608	933	549
		1994	441	122	261	624	698
		1995	333	175	275	579	498
		1996	798	213	134	423	765
		1997	1,102	270	0	0	849
		1998	1,026	138	108	342	923
		1999	1,096	218	78	189	531
		2000	178	65	93	294	292
		2001	49	61	319	849	508
		2002	402	223	0	0	544
		2003	400	186	0	0	408
		2004	1,172	374	0	0	760
		2005	1,231	311	86	272	711
	34 Total		620	420	264	739	653
0 Total			612	414	143	530	689
3	12	1990	763	190	0	0	1022
		1991	716	96	0	0	1064
		1992	1,377	386	0	0	1159
		1993	808	193	0	0	723
		1994	482	154	0	0	796
		1995	653	281	0	0	565
		1996	695	362	0	0	807
		1997	656	317	80	175	775
		1998	1,221	413	0	0	975
		1999	831	172	0	0	571
		2000	340	197	0	0	303
		2001	192	70	20	52	549
		2002	517	162	0	0	544
		2003	454	107	0	0	408
		2004	903	303	73	231	721
		2005	1,055	273	0	0	749
	12 Total		729	386	11	74	733

Continued

Table B2. Grass and Snakeweed (Gusa) yield (kg/ha) and standard deviation (SD) within selected treatments and plots at the Oil Well Site (1990-2005).

Site Name	OW

Trt No.	Plot No.	Year	Grass Average (kg)	Grass (SD)	Gusa Average (kg)	Gusa (SD)	Predicted Grass (kg)
3	24	1990	665	143	0	0	1022
		1991	651	150	0	0	1064
		1992	1,044	409	0	0	1159
		1993	862	271	0	0	723
		1994	403	147	0	0	796
		1995	931	246	0	0	565
		1996	976	242	0	0	807
		1997	1,342	448	0	0	849
		1998	1,456	238	0	0	975
		1999	1,426	279	73	232	543
		2000	325	194	132	418	292
		2001	108	112	352	1,114	533
		2002	575	458	124	393	518
		2003	601	295	0	0	408
		2004	1,543	609	0	0	760
		2005	1,248	421	0	0	749
	24 Total		885	523	43	317	735
	33	1990	805	134	0	0	1022
		1991	683	159	0	0	1064
		1992	1,129	213	0	0	1159
		1993	828	169	0	0	723
		1994	328	171	0	0	796
		1995	438	84	0	0	565
		1996	1,011	229	0	0	807
		1997	1,195	299	0	0	849
		1998	1,321	159	0	0	975
		1999	1,336	298	0	0	571
		2000	273	172	0	0	303
		2001	133	111	0	0	560
		2002	584	496	0	0	544
		2003	380	194	0	0	408
		2004	1,200	420	0	0	760
		2005	788	279	0	0	749
	33 Total		777	450	0	0	741
3 Total			797	460	18	188	736

Continued

Table B2. Grass and Snakeweed (Gusa) yield (kg/ha) and standard deviation (SD) within selected treatments and plots at the Oil Well Site (1990-2005).

Site Name	OW

Trt No.	Plot No.	Year	Grass Average (kg)	Grass (SD)	Gusa Average (kg)	Gusa (SD)	Predicted Grass (kg)
6	9	1991	557	181	70	147	972
		1992	1,044	301	289	588	1023
		1993	548	119	415	876	649
		1994	286	138	258	545	714
		1995	507	109	436	849	485
		1996	782	114	125	226	707
		1997	896	203	70	123	776
		1998	856	209	394	646	818
		1999	631	206	260	557	515
		2000	235	241	147	330	281
		2001	107	51	613	1,344	485
		2002	393	291	0	0	544
		2003	350	201	0	0	408
		2004	635	325	0	0	760
		2005	930	407	0	0	749
	9 Total		584	345	205	574	659
	21	1991	520	130	0	0	1064
		1992	749	189	0	0	1159
		1993	450	79	0	0	723
		1994	302	85	0	0	796
		1995	529	97	0	0	565
		1996	763	122	0	0	807
		1997	764	157	0	0	849
		1998	1,036	123	0	0	975
		1999	906	194	122	387	543
		2000	93	41	0	0	303
		2001	53	73	52	78	529
		2002	158	164	4	13	543
		2003	324	185	0	0	408
		2004	875	438	137	432	720
		2005	758	436	448	901	636
	21 Total		552	360	51	288	708

Continued

Table B2. Grass and Snakeweed (Gusa) yield (kg/ha) and standard deviation (SD) within selected treatments and plots at the Oil Well Site (1990-2005).

Site Name	OW

Trt No.	Plot No.	Year	Grass Average (kg)	Grass (SD)	Gusa Average (kg)	Gusa (SD)	Predicted Grass (kg)
6	29	1991	529	145	0	0	1064
		1992	992	295	0	0	1159
		1993	558	157	0	0	723
		1994	392	72	0	0	796
		1995	429	69	0	0	565
		1996	689	219	0	0	807
		1997	862	188	0	0	849
		1998	1,131	160	0	0	975
		1999	1,061	288	15	46	561
		2000	170	107	98	310	292
		2001	89	53	497	1,572	533
		2002	259	217	0	0	544
		2003	337	184	0	0	408
		2004	1,101	405	0	0	760
		2005	839	272	0	0	749
	29 Total		629	396	41	413	719
6 Total			588	368	99	446	695
10	38	1993	480	117	48	153	689
		1994	283	96	34	109	764
		1995	454	113	51	161	540
		1996	587	137	0	0	807
		1997	832	255	0	0	849
		1998	1,001	251	0	0	975
		1999	470	92	0	0	571
		2000	85	54	0	0	303
		2001	22	26	87	141	509
		2002	139	114	0	0	544
		2003	207	159	0	0	408
		2004	663	334	0	0	760
		2005	1,029	345	0	0	749
	38 Total		481	369	17	80	651

Continued

Table B2. Grass and Snakeweed (Gusa) yield (kg/ha) and standard deviation (SD) within selected treatments and plots at the Oil Well Site (1990-2005).

Site Name	OW

Trt No.	Plot No.	Year	Grass Average (kg)	Grass (SD)	Gusa Average (kg)	Gusa (SD)	Predicted Grass (kg)
10	41	1993	411	66	398	775	621
		1994	241	82	186	540	742
		1995	324	105	0	0	565
		1996	657	192	0	0	807
		1997	720	197	20	63	827
		1998	1,016	371	0	0	975
		1999	500	170	0	0	571
		2000	105	63	0	0	303
		2001	25	41	348	948	507
		2002	120	124	4	13	543
		2003	225	169	0	0	408
		2004	781	345	0	0	760
		2005	921	208	0	0	749
	41 Total		465	365	74	380	644
	45	1993	372	74	515	708	538
		1994	305	140	870	2,121	603
		1995	365	101	47	149	540
		1996	1,023	266	54	169	767
		1997	1,048	220	20	63	827
		1998	1,141	277	39	122	931
		1999	966	177	49	155	545
		2000	130	50	0	0	303
		2001	30	39	70	223	534
		2002	158	141	0	0	544
		2003	244	228	0	0	408
		2004	833	309	0	0	760
		2005	1,257	342	62	196	712
	45 Total		606	470	133	651	616
10 Total			517	408	74	439	637
Grand Total			635	427	84	422	692

Note: Treatment and plot numbers are defined in Figure 2.

APPENDIX C

GRAPHS OF OBSERVED SNAKEWEED AND GRASS BIOMASS COMPARED WITH PREDICTED VALUES

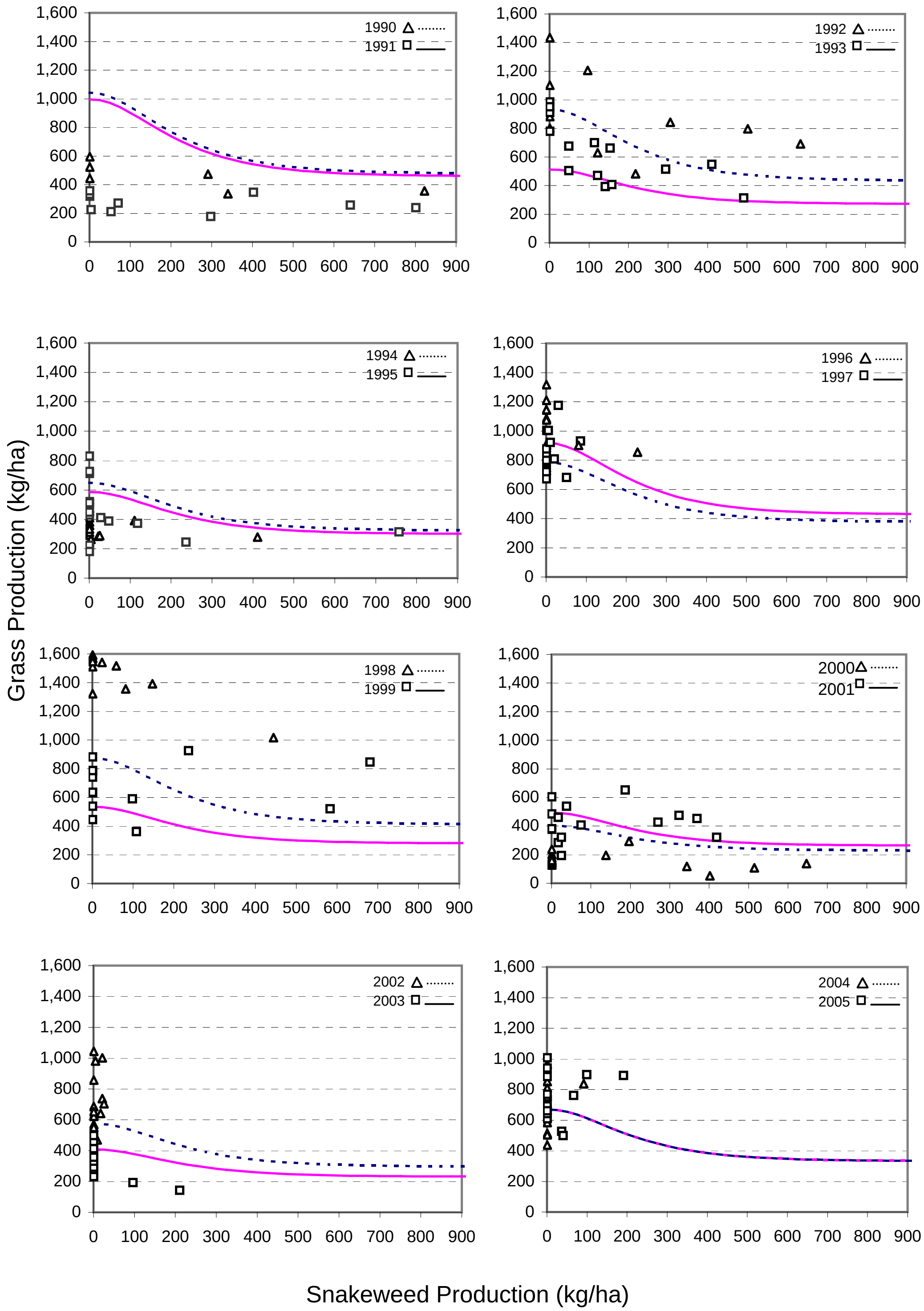


Figure C1. Observed broom snakeweed and grass biomass compared with predicted values from Model 1 (SM1) at the South House Study site (1990-2005).

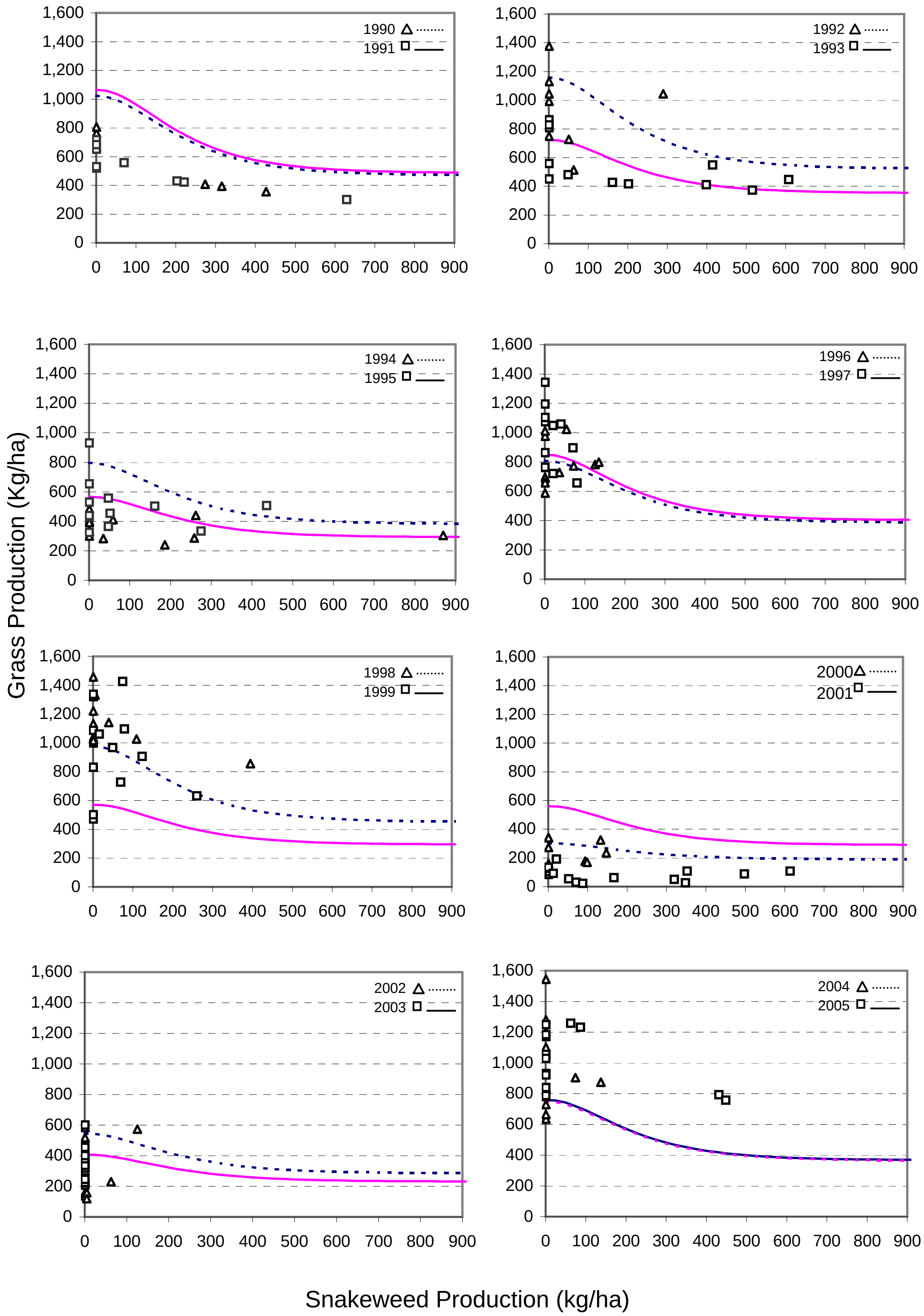


Figure C2. Observed broom snakeweed and grass biomass compared with predicted values from Model 1 (SM1) at the Oil Well Study site (1990-2005).

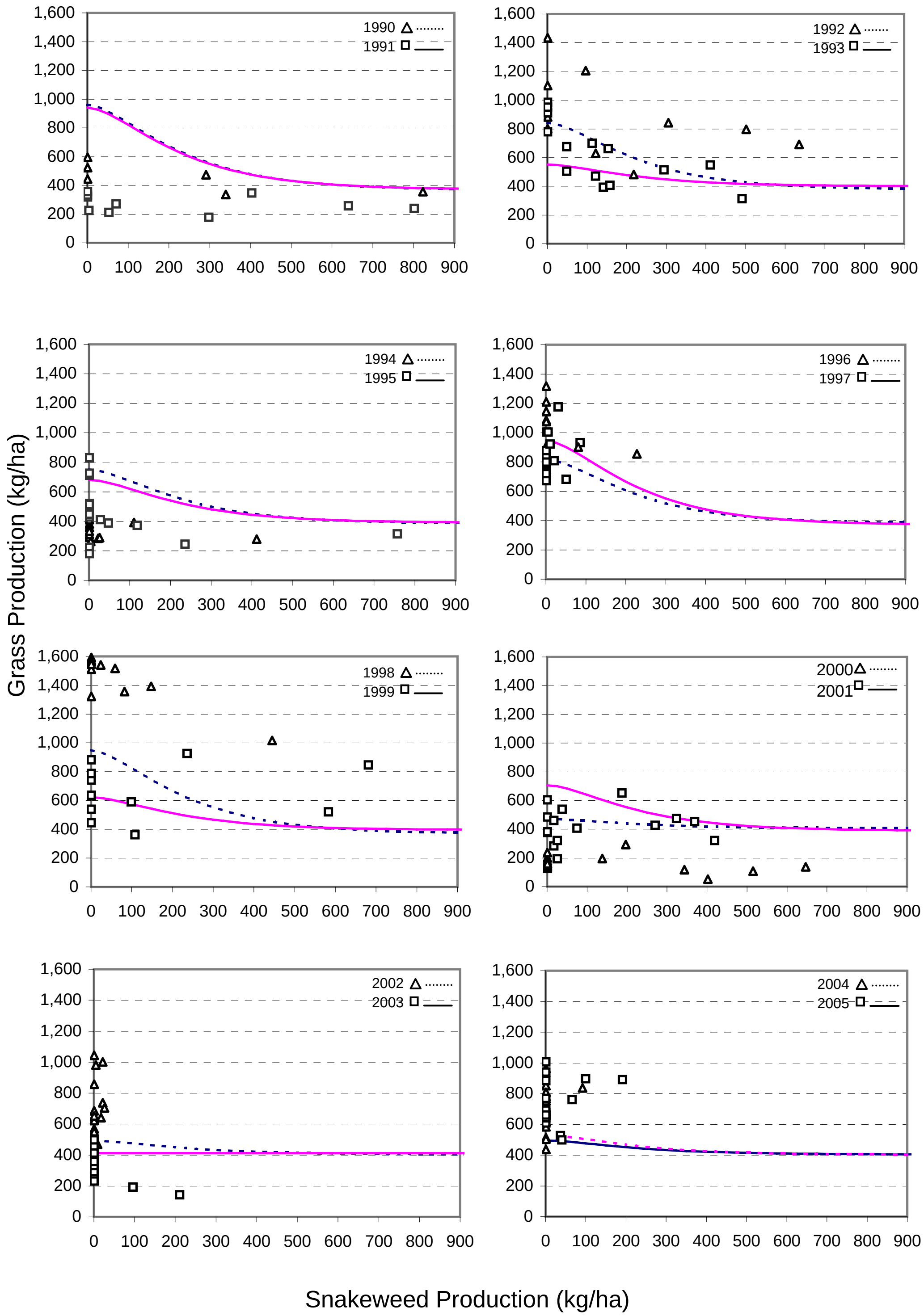


Figure C3. Observed broom snakeweed and grass biomass compared with predicted values from Model 2 (SM2) at the South House Study site (1990-2005).

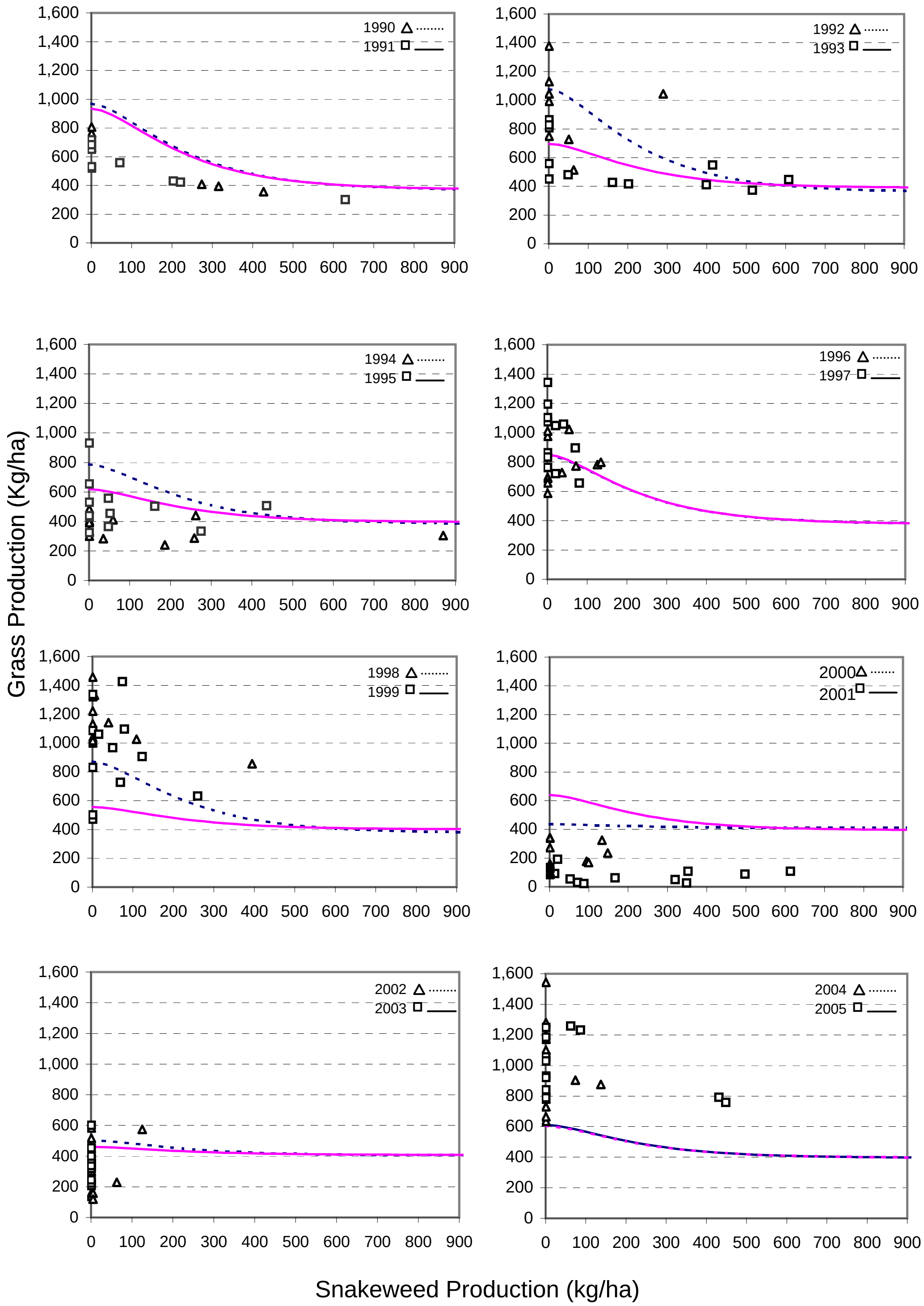


Figure C4. Observed broom snakeweed and grass biomass compared with predicted values from Model 2 (SM2) at the Oil Well Study site (1990-2005).

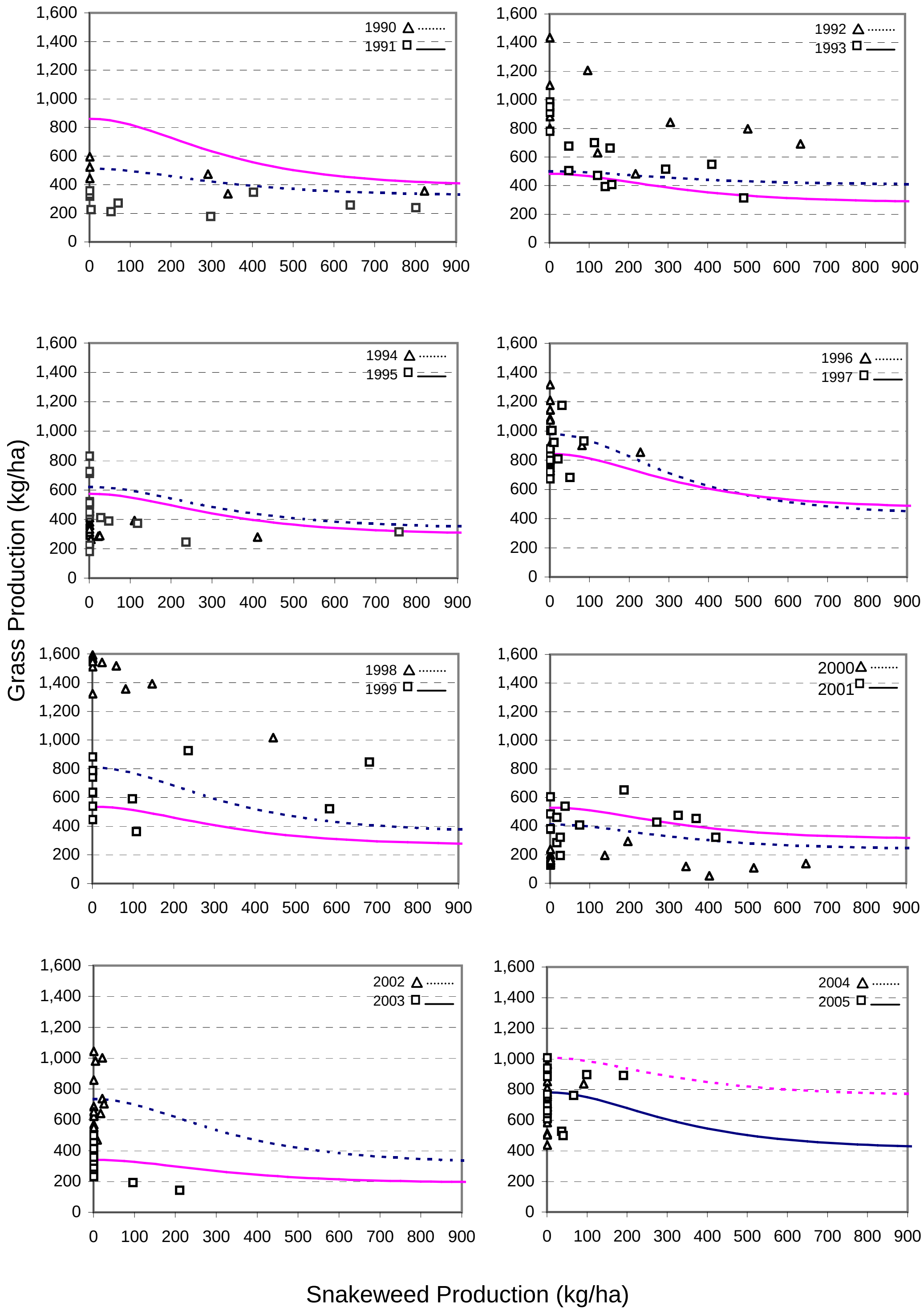


Figure C5. Observed broom snakeweed and grass biomass compared with predicted values from Model 3 (Rainfall) at the South House Study site (1990-

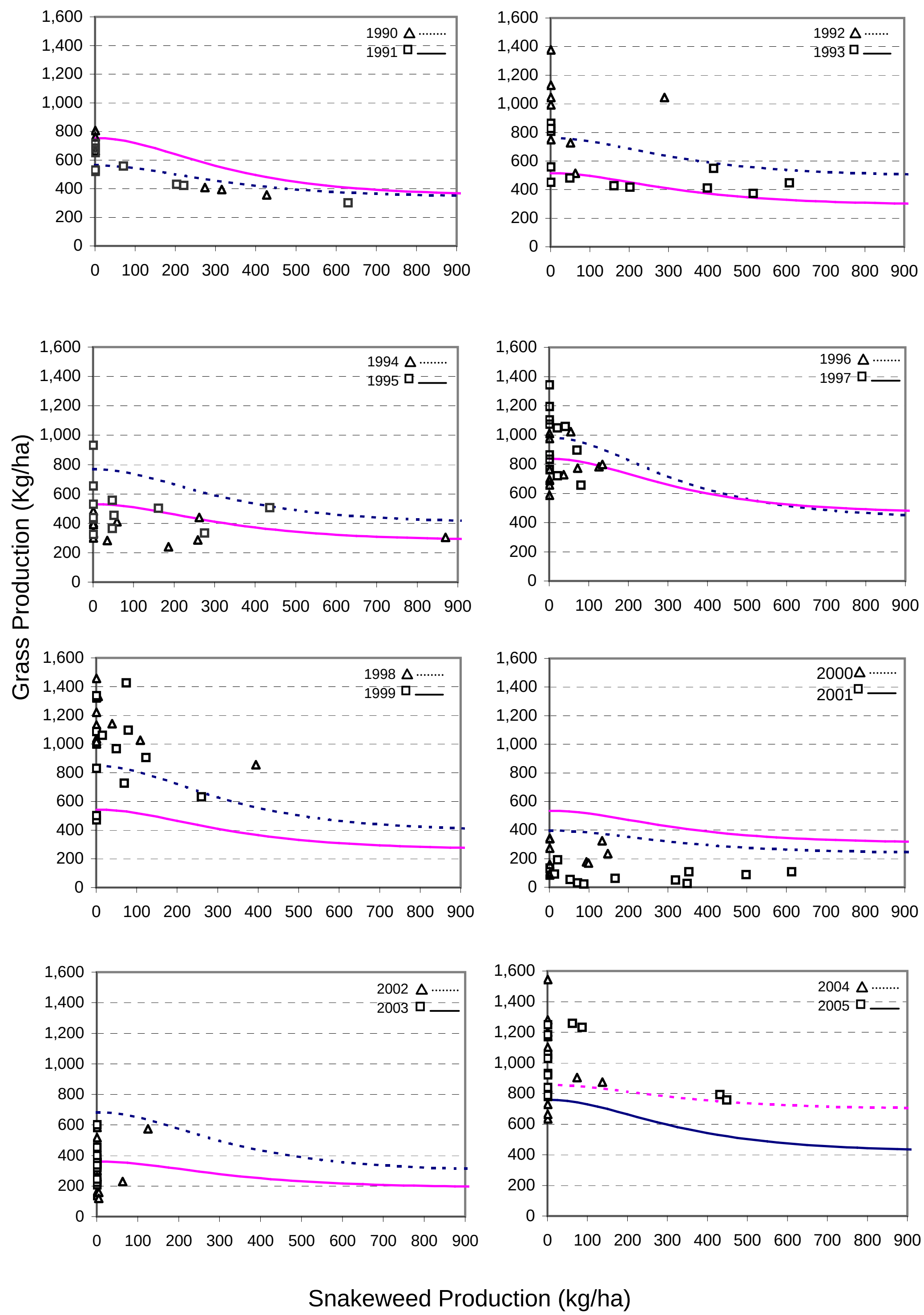


Figure C6. Observed broom snakeweed and grass biomass compared with predicted values from Model 3 (Rainfall) at the Oil Well Study site (1990-2005).

APPENDIX D

MONTHLY RAINFALL ON THE CORONA RANCH

Table D1. Monthly rainfall (mm) on the Corona Ranch.

Average between South House and Oil Well sites

		Year															
Month	**30 Yr Avg**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
Jan	16	14	5	33	18	2	8	4	4	1	0	0	10	4	0	7	123
Feb	15	23	4	11	13	2	7	6	28	9	0	0	18	9	6	13	97
Mar	19	28	11	31	6	13	15	2	3	29	0	25	17	4	10	3	17
Apr	20	22	0	14	4	12	9	1	54	13	15	7	5	1	8	110	7
May	26	18	34	136	18	102	17	0	30	0	36	1	34	0	14	5	60
Jun	35	6	27	20	37	20	23	76	89	0	37	53	17	18	10	39	12
Jul	69	68	91	32	45	50	50	122	39	66	85	10	41	92	34	55	12
Aug	77	0	89	44	42	76	62	128	106	98	41	13	58	42	26	85	49
Sep	45	41	67	14	7	40	46	53	64	35	31	1	30	80	9	23	33
Oct	26	14	18	18	33	29	0	33	17	75	8	76	6	29	27	51	29
Nov	13	10	35	4	14	19	2	8	13	5	0	10	35	8	14	18	0
Dec	19	7	61	6	4	19	6	0	24	9	4	6	5	21	7	9	0
Total	388	253	441	364	242	384	246	432	470	340	257	201	276	308	165	418	438

South House site

		Year															
Month	**30 Yr Avg**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
Jan	16	14	5	33	19	2	8	4	5	0	0	0	9	5	0	7	123
Feb	15	23	4	11	13	2	7	5	27	5	0	0	18	9	6	13	97
Mar	19	28	10	33	8	13	15	2	3	26	0	23	15	5	10	4	17
Apr	20	22	0	13	2	10	8	1	53	12	14	7	6	1	8	105	7
May	26	18	34	136	17	96	20	0	32	1	41	1	39	0	17	6	55
Jun	35	6	30	16	33	19	23	76	92	0	37	52	16	18	12	30	24
Jul	69	58	91	1	48	46	47	122	39	69	83	10	45	89	24	50	23
Aug	77	0	110	20	42	56	71	128	106	95	39	13	45	46	31	101	67
Sep	45	41	67	17	6	39	48	53	64	37	33	1	37	88	8	23	31
Oct	26	14	18	19	25	28	0	33	17	71	7	80	7	29	28	48	28
Nov	13	10	34	4	15	19	2	8	13	5	0	10	38	10	14	17	0
Dec	19	7	61	5	4	19	5	0	24	8	4	5	6	23	8	9	0
Total	388	243	464	308	232	349	254	431	473	330	258	202	282	322	165	413	472

Oil Well site

		Year															
Month	**30 Yr Avg**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
Jan	16	14	5	33	17	3	8	3	4	2	0	0	11	3	0	8	123
Feb	15	23	4	11	12	2	7	7	28	13	0	0	18	9	6	12	97
Mar	19	28	11	28	5	14	15	2	3	31	0	26	19	3	9	3	16
Apr	20	22	0	15	6	13	10	1	55	13	17	7	5	1	8	115	7
May	26	18	34	136	20	108	15	0	29	0	30	0	28	0	10	3	65
Jun	35	6	24	25	40	21	24	76	85	0	38	55	18	18	8	48	0
Jul	69	78	91	62	42	53	53	122	39	62	87	10	37	95	44	60	0
Aug	77	0	68	68	42	96	53	128	106	101	43	13	71	38	21	69	30
Sep	45	41	67	12	8	42	43	53	64	33	29	1	24	72	11	22	35
Oct	26	14	18	18	42	30	0	33	17	79	9	71	5	29	27	54	30
Nov	13	10	36	5	14	19	2	8	13	5	0	10	31	6	14	19	0
Dec	19	8	61	8	4	19	6	0	24	10	4	6	5	20	6	9	0
Total	388	263	419	420	252	419	237	433	466	350	257	200	270	294	164	422	403

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