MEASURING AND SIMULATING SOIL WATER AND VEGETATION DYNAMICS IN SAGEBRUSH-STEPPE RANGELANDS

A thesis

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Abstract

Plant growth is important as forage and cover for livestock and wildlife. It reflects the productivity of communities and is a way to track change. Forecasting plant growth could change land management in a positive way. A direct way to forecast plant growth is through measuring and simulating the water stored in the soil. The objectives of this study were to evaluate Soil Ecohydrology Model (SEM) soil moisture simulations and investigate the use of SEM yield indices for forecasting plant growth. The use of the Accupar ceptometer (Decagon, Pullman, WA) or lightbar for measuring leaf area index (LAI) in sagebrush steppe rangelands and the collection of calibration and validation criteria for vegetation production forecasting models including percent cover, estimated standing biomass, and yield were also investigated. SEM soil moisture simulations were compared to measured soil moisture data over a 27-32 year study period. Lightbar LAI data were compared to LAI data collected using the point-intercept method. Comparisons were made between LAI and yield, LAI and cover, and cover and biomass. SEM soil moisture simulations followed the general trends in soil moisture throughout the year with a slight trend towards underestimation. The success of SEM soil moisture simulations indicated that it may be a valid tool for forecasting plant growth. Using the methods presented in this study the lightbar is an inaccurate, imprecise method of measuring LAI in sagebrush steppe rangelands. The methods used in this study to collect calibration and validation criteria for vegetation production forecasting models provided important site-descriptive data and valuable comparative analyses that indicated LAI and yield and LAI and cover are well-correlated, but cover and biomass are only weakly correlated. Simulating soil moisture and forecasting yield could be valuable tools for ranchers, restoration professionals, and land management agency personnel. Further research is needed to create and implement a vegetation production forecasting system.

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Introduction

Plants require water to grow and many researchers have explored the relationship between plant growth and water. Briggs and Shantz (1914) studied the relationship between transpiration and plant growth and de Wit (1958) expanded on their work by developing a plant production forecasting equation. Other researchers have studied the relationship between precipitation and growth and tried to forecast plant growth from precipitation (Sneva and Hyder, 1962; Hanson et al., 1983; Hillel, 1998). Precipitation can be patchy and difficult and expensive to measure, and plant transpiration is highly dependent on plant available water in the soil. A more direct way to forecast plant growth is through measuring and simulating the water stored in the soil.

Plant growth is important as forage and cover for livestock and wildlife. It reflects the productivity of communities and is a way to track change. Forecasting plant growth could change land management in a positive way. Ranchers and other land managers rely on plant growth each year to meet financial and land management objectives. When ranchers write their annual grazing plan it is common to assume that each year will be an average production year and adjust based on how much the plants actually produce. An estimate of plant growth that is more effective than using the average could provide ranchers with information to support and improve land and asset management. It could help restoration personnel plan and implement more effective, successful restoration projects and reduce fiscal waste. Estimates of plant growth could benefit land management agencies and their personnel by providing scientifically-based decision making criteria and subsequently the opportunity for stronger legal defenses.

This thesis reviews the initiation of a project with a much larger scope. The project began with the installation of climate and soil moisture monitoring equipment. In the first study, a focus was placed on testing Soil Ecohydrology Modle (SEM) soil moisture simulations as a step towards using SEM to forecast yield. Leaf area index is an important model input and the second study addresses methods of measuring leaf area index in sagebrush-steppe rangelands. The third study reviews the methods used for this project and analyses the data that resulted. The next step for this project is to begin testing model yield forecasts and to develop a decision making system with the end-user, hands-on land managers, in mind.

LITERATURE CITED

Briggs, L.J. and H.L. Shantz. 1914. Relative water requirement of plants. *Journal of Agricultural Resources* 3:1-63

Hanson, C.L., R.P. Morris, and J.R. Wight. 1983. Using precipitation to predict range herbage production in southwestern Idaho. *Journal of Range Management* 36:766-770

Hillel, D. 1998. Environmental soil physics. San Diego, CA, USA: Elsevier 771p.

Sneva, F.A. and D.N. Hyder. 1962. Estimating herbage production on semiarid ranges in the intermountain region. *Journal of Range Management* 15:88-93

Chapter 1

Simulation of long-term soil water dynamics: Implications for rangeland productivity

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ABSTRACT

Many land managers are dependent on aboveground net primary production, or plant growth, for the success of their business and to meet land management objectives. For these land managers having an estimate of plant growth each year before peak standing crop is reached would aid their ability to make informed management decisions. In this study the Soil Ecohydrology Model (SEM) was used to simulate soil moisture and forecast plant growth using a yield index at three sagebrush steppe sites, representing a range of vegetation and climate conditions. SEM is a capacitance parameter model that uses a water budget equation to simulate changes in soil moisture and a modification of the de Wit equation to forecast yield. Model simulated soil moisture data were evaluated using long term measured soil moisture data. Yield estimates were forecast using the yield index from SEM and NRCS ecological site descriptions. Results showed no significant difference between measured and simulated total soil water (S_w) values at the three sites. Correlation between measured and simulated S_w datasets was strong at all sites. Yield estimates reflected increases and decreases in annual precipitation. Access to reliable, accurate yield forecasts would aid land managers of all types, including ranchers, government agency personnel, and restoration professionals by providing enhanced means for well-informed decision making.

INTRODUCTION

For many rangeland managers annual aboveground net primary production, or plant growth, is very important to maintain a successful business operation and to meet land management

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objectives. For these land managers, having a dependable, accurate estimate of plant growth before peak standing crop would be helpful. A common strategy is to assume every year is an average year and make changes in management as needed (Hanson et al., 1983; Holecheck, 2001). This strategy does not allow land managers to plan ahead, and often, leaves little time to prepare for below average years or to take advantage of above average years. The benefit of a model or system that dependably and accurately forecasts plant growth has been previously recognized by many scientists, as evidenced by the research that has been done defining the relationship between environmental factors and plant growth (Briggs and Shantz, 1914; de Wit, 1958; Tanner and Sinclair, 1983), reviewed below.

Some of the first research defining the relationship between environmental factors and plant growth was conducted in the early twentieth century by Briggs and Shantz (1914) and focused on defining the relationship between transpiration and plant growth using crop plants grown in pots (Tanner and Sinclair, 1983). De Wit (1958) expanded on the initial work of Briggs and Shantz (1914) when he developed the following equation that defines the relationship between plant growth and transpiration in arid and semi-arid climates:

$$\frac{Y}{T} = \frac{m}{T_{max}} \qquad \text{(Equation 1)}$$

where Y represents plant growth or yield and is total dry matter mass per area, T is total transpiration per area during growth to harvest, T_{max} is mean daily free water, or potential evaporation for the same period, and m is a crop factor dependent on variety and species (Hanks, 1983; Kirkham, 2005). The basic assumption behind this equation is that, in water limited environments, vegetative yield is directly proportional to the amount of transpiration and inversely proportional to the evaporative demand. A review of six yield forecasting models used on crops found that five out of six of the models used the de Wit equation or a variant to quantify plant stress and subsequent growth rates based on transpiration levels (Saseendran et al., 2008).

Plant growth has also been correlated with precipitation (Sneva and Hyder, 1962; Hillel, 1998) and plant growth models have been developed that use precipitation to forecast plant growth (Hanson et al., 1983). The progression from using transpiration to forecast plant growth to using precipitation to forecast plant growth was logical, as precipitation directly affects how much water is available to plants for transpiration and precipitation is easier and less expensive to measure on a large scale than transpiration. Plant growth models developed to forecast plant growth from precipitation generally rely on past precipitation amounts to develop equations that describe the relationship between growth and precipitation. Often they focus on the precipitation received within a certain time period, such as April, May and June (Sneva and Hyder, 1962), which occurs during active plant growth.

Precipitation, however, can be patchy (Hanson et al., 1983) and difficult and expensive to measure accurately, especially when it falls in the form of snow. Factors such as evaporation potential, soil permeability, field capacity, litter layer, range condition, season, precipitation type and intensity, annual variation in precipitation received, vegetation physiognomy, wind speed, soil surface condition, soil temperature and soil water content affect how much precipitation actually infiltrates the soil profile and becomes available to plants (Hillel, 1998; Miller and Gardiner, 1998; Barbour et al., 1999; Gates et al., 2003). These factors make it difficult to create a model that is widely applicable across diverse field sites (Hanson et al., 1983).

It has been suggested that measuring and modeling volumetric water content, or soil moisture, is a more direct, accurate, and applicable way to forecast plant growth that could be used across a diverse set of field sites. The measurement of soil moisture has become easier, more affordable and more accurate as technology has progressed (e.g., Seyfried and Murdock, 2004), making the use of soil moisture as a way to calibrate and validate plant growth forecasting models more accessible and economical for broad scale use.

Published forage production data are rare for sagebrush-steppe environments, and these are usually short term. As a result, assessment of production conditions is highly subjective. There is little basis, for example for estimates of “average” yield conditions. An alternative to measuring yield is to simulate it using plant production models. The modeling approach has the added advantage of providing a means of projecting yields for a wide spectrum of conditions.

In sagebrush-steppe rangelands the majority of effective precipitation is usually received in fall, winter and spring (Sneva and Hyder, 1962), when plants are dormant or just entering the active stages of plant growth. That means vegetation in sagebrush-steppe rangelands often relies on water stored in the soil from previous precipitation events to supply the water necessary for plant growth. This type of growing condition, where plants rely on precipitation that falls outside the active growing season is uniquely suited for testing the vegetation forecasting models that rely on soil moisture to forecast vegetation production. Production forecasts can be made from stored soil moisture that was simulated or measured. This method of vegetation production forecasting would be less applicable in areas where precipitation more commonly falls during active plant growth.

The Soil Ecohydrology Model (SEM) forecasts plant growth by using a water budget equation (Tanner and Sinclair, 1983) to simulate changes in soil moisture and the de Wit (1958) equation to create a yield index (T/T_{max}), from which plant growth can be calculated. SEM is one of many plant growth forecasting models that have been developed for use in research or as a decision support system. Plant growth forecasting models have been developed for use with crops, in forests and on rangelands. However, few of the models focus on forecasting plant growth on rangelands. Two highly published models that forecast plant growth on rangelands, include the Simulation of Production and Utilization on Rangelands (SPUR) model (Foy et al., 1999) and the Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model (Kiniry et al., 1992). SEM was chosen for use in this study over other rangeland plant growth forecasting models because land managers were the intended end-user of the research. SEM is a simple model that facilitates a focus on the relationship between soil moisture and yield. The required model inputs are simple and site specific input criteria can be easily accessed online at the National Oceanic and Atmospheric Administration website and the United States Department of Agriculture (USDA), Natural Resource Conservation Service (NRCS) website, among others. In addition, SEM has recently been shown to accurately describe soil water balance in sagebrush rangelands (Seyfried et al., 2009). Although direct measurements of transpiration were not made in that study, the accurate simulation of soil water balance indicates that transpiration was probably simulated with some accuracy. Models that forecast plant growth on rangelands that were too complex and not practical for the end-user were not used in this study.

The objectives of this study were to: (1) evaluate the SEM model in varied sagebrush steppe environments over a 27 to 32 year period in terms of soil water balance and (2) to investigate the potential use of SEM-calculated yield indices to forecast yield from measured soil water. The results will provide valuable information concerning interannual yield variability and the critical relationships between yield and soil moisture in sagebrush steppe rangelands.

METHODS

Site Description

Soil moisture data were collected at three sites on the Reynolds Creek Experimental Watershed in Owyhee County of southwestern Idaho. The three sites, located at different elevations, represent differing climatic conditions and vegetative communities. At an elevation of 1190m (4,000 feet), the Flats site, had a mean annual precipitation of 270 mm (23.5 inches) and a mean annual temperature of 9°C (23°F). The soil at ID-Flats was mapped as a Hardtrigger-Enko complex (2 – 15% slopes). Dominant species were Wyoming Big Sagebrush, Shadscale Saltbush (*Atriplex confertifolia* [Torr. & Frem.] S. Watson), Bottlebrush Squirreltail (*Elymus elymoides* [Raf.] Swezey), and Sandberg Bluegrass (*Poa secunda* J. Presl). The second site, Nancy's Gulch (NG), was at an elevation of 1400m (4,590 feet) and had a mean annual precipitation of 300 mm (30 inches) and a mean annual temperature of 9°C (23°F). ID-NG soil was mapped as the Arbidge-Owsel-Gariper complex (1 – 15% slopes). Vegetation at ID-NG was characterized by Wyoming Big Sagebrush, Bluebunch Wheatgrass *(Pseuodroegneria spicata* Pursh), Bottlebrush Squirreltail, and Sandberg Bluegrass as the dominant species. ID-Lower Sheep Creek (LSC), the study site in Idaho at the highest elevation, 1627m (5,340 feet,) had a mean annual precipitation of 340 mm (34 inches) and a mean annual temperature of 8°C (22°F) during the study period. The soil was mapped as a Vitale-Itca-Rubble land complex (2 - 60% slopes). Dominant species at ID-LSC are Low Sagebrush (*Artemisia arbuscula* Nutt.), Lupine (*Lupinus* L. sp.), Milkvetch (*Astragalus* L. sp.) and Sandberg Bluegrass.

Data Collection

The measured soil moisture data were collected using a neutron moisture meter over a 27-32 year period; the length of data collection varies by location. The neutron moisture meter scatters fast moving neutrons and counts the number of slow neutrons that return and collide with the probe. Since neutrons are about the size of a hydrogen ion, when a neutron collides with a hydrogen ion it slows down. Therefore, the number of slow neutrons that return to the probe and are counted represents the amount of hydrogen found in the portion of soil being measured. The overwhelming source of hydrogen in the soil is water, so the number of slow neutrons counted closely approximates the percentage of water in the soil being measured (Hignett and Evett, 2002).

Measurements with the neutron moisture meter were taken in an aluminum access tube; this method allows for repeated in situ measurement, without disturbing the surrounding soil. When the neutron moisture meter is placed in the soil it measures a large volume of soil, in a sphere with a 15 cm radius. Measurements were completed at 15 cm, 30 cm, 60 cm, and 90 cm. The SEM model simulates soil moisture at complimentary depths of 5 cm, 15 cm, 30 cm, 60 cm, 90 cm and 120 cm. The values at 120 cm were disregarded in this study due to a lack of deep drainage and very little to no change from season to season at the study sites. Total soil water is calculated for measured and simulated soil moisture using soil moisture values from each depth. The diameter of the projected spheres measured at 15 and 30 cm is 22.5 cm. The diameter of the projected spheres measured at 60 and 90 cm is 30 cm. Each soil moisture value was multiplied by the diameter of the sphere associated with it and then all values were summed to indicate the total soil water storage (S_w), in centimeters. For more information see Seyfried et al. (2001).

The first neutron moisture meters that were utilized, measured soil moisture higher than the newer meters that replaced them. To facilitate side-by-side comparison of the data, the measured soil moisture that was higher than the plant extraction limit (PEL) was subtracted from the total measured amount of soil moisture at each depth. The lowest measured soil moisture values were considered outliers and therefore to contain significant error either due to instrument measurement variability or operator error and were not used to determine PEL. As a result when PEL was subtracted from the measured soil moisture, there were some negative values. Because the calculations and adjustments made to the simulated and measured data, S_w could be called plant available water. The data that were collected over the course of the study period show that plants at the study sites use all available water in the soil, every year, even in extreme above average precipitation years.

Data collection protocol dictated that measurements be collected every two weeks, year round. However, the study period of 27 – 32 years was an extended period of time and a number of issues arose that, at varying times, prevented the data from being collected on schedule. As a result, soil moisture data were not consistently collected every two weeks.

Model Description

The SEM was used to simulate soil moisture conditions at the study sites described above. The SEM is characterized as a capacitance parameter model because it uses a water-balance approach to simulate soil moisture (Wight et al, 1986 and Wight and Hanks, 1981). SEM was developed by Wight and Hanks (1981) and originally named the Ekalaka Range Hydrology and Yield Model (ERHYM-II). The SEM was adapted from its original format by Seyfried (2003; Seyfried et al., 2009). ERYHM-II was used extensively in a variety of climates to model evapotranspiration, simulate soil moisture dynamics, and forecast yield (Conner 1994; Cooley and Roberston, 1984; Weltz and Blackburn, 1993; Wight et al., 1984; Wight and Hanson, 1990; Wight and Hanson 1991).

The SEM requires weather conditions and soil parameters as inputs. Weather inputs include minimum and maximum daily temperature, daily precipitation, and daily solar radiation. The weather data used as an input for the SEM model were collected at each of the sites described above (Hanson, 2001; Hanson et al., 2001). Soil parameters include field capacity, fine earth to coarse fragment ratio, the plant extraction limit, also known as permanent wilting point, volumetric water content at soil saturation, and plant rooting depth. SEM outputs include the weather data that was an input, simulations of evapotranspiration, soil moisture at multiple depths, and a yield index. The yield index is calculated from a modification of the de Wit equation (Wight and Hanks, 1981):

$$\frac{T}{T_p} = \frac{Y}{Y_p} \qquad \text{(Equation 2)}$$

where T is plant transpiration, T_p is potential transpiration, Y is yield and Y_p is maximum potential yield. The yield index was calculated from the left side of the equation T/T_p.

Yield Index Conversion

The SEM outputs two yield indices, a daily yield index and a cumulative yield index; both are a number between zero and one and reflect potential evapotranspiration. The daily yield index represents potential daily yield based on plant water demands and the cumulative yield index (CYI) is a cumulative measure of YI, that represents potential annual yield to date. Because the CYI is a cumulative measure of YI it fluctuates with the increases and decreases in soil moisture throughout the year as a reflection of potential evapotranspiration. When S_w is low the CYI is low, when S_w is high, the CYI is high, therefore a specific date must be chosen to represent peak standing crop; the point in time at the end of each growing season when plants are still active, not dormant, but have stopped growing because soil moisture is insufficient to support significant continued growth. For this study, June 1 was chosen to represent peak standing crop at the Flats, June 15 was chosen to represent peak standing crop at Nancy's Gulch, and July 1 was chosen to represent peak standing crop at Lower Sheep Creek. It is acknowledged that peak standing crop does not occur on the same day every year, especially over an extended time period of time, as in this study. However, to maintain objectivity and repeatability the same date, was used to represent peak standing crop at each site during each year of the study. The 15 day offset between each site accounts for the delay in the start of plant growth as differences in elevation among the sites. Yield was calculated using Y_p values obtained from the USDA-NRCS ecological site description (ESD) for each site and the CYI output by SEM using the following ratio:

$$\frac{CYI_p}{Y_p} = \frac{CYI}{Y} \qquad \text{(Equation 3)}$$

where CYI_p represents the highest forecasted yield index at each site and Y_p represents the maximum yield measured or estimated at each site. CYI is the cumulative yield index value produced by the model and Y is the yield for the year of interest. The ratio was solved using cross-multiplication to estimate annual yield for each year of interest. ESD yield estimates were compared to yield values collected at Reynolds Creek Experimental Watershed and documented in an interagency report to determine validity; site specific ESD yield estimates are reasonable at the Flats, Nancy's Gulch and Lower Sheep Creek (Hanson et al., 1994)

Data were analyzed using Systat 13 and Microsoft Excel. Initial analysis was done by graphing simulated S_w values versus measured S_w values for all sites. Analyses of variance (ANOVA) were used to determine if there was a significant difference between measured and simulated S_w data. Pearson's correlation was used to define the correlation between the measured and simulated S_w values. A Tukey pairwise mean comparison honestly significant difference (HSD) test was used to examine the relationship between the measured and simulated S_w means. Data means were also directly compared using graphs. The Nash-Sutcliffe Index is a model efficiency factor that was used to measure how well the simulated data fit the measured data. Confidence intervals were calculated to define precision within datasets. Potential annual variation in yield and precipitation was examined using forecasted yield values that were compared to annual precipitation amounts.

RESULTS

Result from the initial graphs showed a strong relationship between measured and simulated S_w data with r^2 values above 0.75 at all sites. Simulated S_w values generally reflect increases and decreases in soil moisture observed through measured S_w values (Figures 1, 2, 3, 4, 5, and 6 and Table 1).

The analysis of variance (ANOVA) was used to determine if there was a significant difference between measured and simulated S_w data. The p-value was greater than 0.05 for all sites indicating there was no significant difference between measured and simulated S_w data at the Flats, Nancy's Gulch and Lower Sheep Creek. The MSE for the Flats was 9.685, the MSE for Nancy's Gulch was 17.319 and the MSE for Lower Sheep Creek was 27.361.

A Tukey HSD was used to examine the relationship between the means of the measured and simulated S_w values. The p-value was greater than 0.05 for all sites indicating there was no significant difference between measured and simulated S_w data at the Flats, Nancy's Gulch and Lower Sheep Creek. Data means for measured and simulated datasets were very similar at all sites (Figure 7).

Pearson's correlation was used to define the correlation between the measured and simulated S_w values. The Pearson's coefficient was 0.870 at the Flats, 0.901 at Nancy's Gulch, and 0.925 at Lower Sheep Creek indicating a strong correlation between measured and simulated S_w values at all study sites.

The Nash-Sutcliffe efficiency factor was used to determine how well the model simulated S_w values. The Nash-Sutcliffe index was 0.736 at the Flats, 0.755 at Nancy's Gulch, and 0.814 at Lower Sheep Creek indicating that the model did a relatively good job of representing measured soil moisture values.

Forecasted yield values (Figure 10 and Table 1) reflected annual variation in precipitation amounts and site to site differences in annual mean precipitation. They also revealed large variation from year to year, presenting a unique view of interannual variation to which plants, animals and land managers must adapt.

DISCUSSION

It has been shown that transpiration is related to yield, and SEM calculates transpiration from soil moisture, so it is important for model simulations to be relatively accurate at all depths. However, S_w directly reflects how much water is in the soil and available for plant uptake. Therefore, accurate simulation of S_w is critical to accurate yield forecasts. It should be noted, that comparison of these results with other studies is not straightforward because this study covers a much longer time frame than most studies focused on simulating soil moisture. A two year study was done with SEM simulating soil moisture and much higher r^2 values were achieved (Seyfried, 2009).

Error present in the data can be separated into three main categories of potential sources: problems with the input data, model inadequacies, and problems with the comparison data. Potential sources of error in the input data could be inaccurately collected weather data from precipitation, solar radiation, or wind. Soil attributes play a key role in model simulations of water storage and plant water uptake; soil attributes that do not fit actual site characteristics could cause poorly simulated soil moisture values.

There is considerable variability in soil water over short distances (Seyfried et al., in review) which SEM may not adequately simulate. SEM treats all leaf area the same, regardless of species or phenology which may cause inaccurate model simulation of plant water uptake. SEM also does not account for overland flow or blowing snow. It is possible for a model to simulate the effects of overland flow and blowing snow, but it requires a model more complex than SEM with an emphasis on hydrology and snow dynamics.

Over the course of the study period there have been a variety of operators and neutron moisture meters, both operating in all types of weather conditions; it is expected that this has resulted in more variability in the data than would be expected in a more typical one to two year study. Additionally, neutron meter calibrations are based on data from two sites, so there may be variation in the data due to instabilities in the calibration. In some cases during the spring, measured S_w values exceed measured precipitation values. This could be a result of snow piling up near the access tube or overland water flow towards the access tube.

Despite all the potential sources of error, the model described most of the variability seen in S_w and captured the basic dynamics of soil moisture throughout the water year. S_w was simulated within 0.25 cm of measured values. The model simulated all sites and depths with similar accuracy; no significant variation based on depth was observed in the data. SEM also simulated values close to the measured values seen at both high and low soil moisture extremes.

A unique view of inter-annual yield variation is seen in forecasted yield values that range from 122 kg/ha at the Flats in 1992 to 1,233 kg/ha at Nancy’s Gulch in 1998. A nine-fold range was seen in forecasted yield values from the Flats. Forecasted yield values were considered 65% accurate based on comparisons between simulated total soil water values and forecasted yield values.

In light of the satisfactory results SEM has exhibited when simulating soil moisture, it is possible that SEM could be just as successful forecasting yield. A yield forecast that was more reliable than using the average could have a major influence on land management. An important step forward for land managers from all backgrounds would be for yield forecasts from SEM to help them prepare for the variation in yield seen at sites like the Flats each year.

IMPLICATIONS

SEM successfully simulated soil moisture values over a thirty year time-span and captured the basic soil dynamics. No significant difference was found between measured and simulated S_w values at the Flats, Nancy's Gulch, or Lower Sheep Creek. Overall, the SEM model holds promise for producing accurate yield forecasts that land managers could use for more informed decision making.

The ability to accurately forecast plant growth prior to and throughout the growing season could revolutionize land and livestock management. Private land owners whose livelihood depends on the yearly growth of range plants would be able to make more informed decisions as they strive to meet land management and financial objectives. The freedom of meeting or exceeding financial objectives as a result of an improved, better informed decision making process would provide land managers with the confidence to make objective decisions regarding the land and how to best achieve management objectives. The ability to forecast plant growth would allow restoration personnel to plan restoration projects at a time when the project is most likely to be successful. The improved ability to plan and adapt to the challenges restoration personnel face would provide the opportunity for more effective spending on restoration projects and reduced fiscal waste. A plant growth forecasting system would give land management agency personnel, including the Bureau of Land Management (BLM) and the U.S. Forest Service (USFS), the ability to use scientifically defensible decision making criteria to determine stocking rates during drought. A highly defensible, scientifically based land management decision making system would provide the opportunity for stronger legal defenses against lawsuits brought against federal, state, and other land management agencies.

LITERATURE CITED

Barbour, M.G., J.H. Burk, W.D. Pitts, F.S. Gilliam, and M.W. Schwartz. 1999. Terrestrial plant ecology. Menlo Park, CA, USA: Benjamin/Cummings an imprint of Addison Wesley Longman, Inc. 649 p.

Briggs, L.J. and H.L. Shantz. 1914. Relative water requirement of plants. *Journal of Agricultural Resources* 3:1-63

Conner, R.J. 1994. Assessing the socioeconomic impacts of climate change on grazing lands. *Climatic Change* 28:143-157

Cooley, K.R. and D.C. Roberston. 1984. Evaluating soil water models on western rangelands. *Journal of Range Management* 37:529-534

de Wit, C.T., 1958. Transpiration and crop yields. Wageningen, The Netherlands: ‘s-Gravenhage: Ministerie van Landbouw (cited in Kirkham, 2005, p. 483)

Foy, J.K., W.R. Teague, and J.D. Hanson. 1999. Evaluation of the upgraded SPUR model (SPUR2.4). *Ecological Modelling* 118:149-165

Gates, R.N., A.J. Smart, and P.E. Reece. 2003. The journey to recovery of the range after drought. In: Proceedings, the range beef cow symposium XVIII; 9-11 December 2003; Mitchell, Nebraska, USA: The Range Beef Cow Symposium XVIII

Hanks, R.J. 1983. Yield and Water-Use Relationships: An Overview. *In*: H.M. Taylor, W.R. Jordan, and T.R. Sinclair [EDS]. Limitations to efficient water use in crop production. Madison, WI, USA: American Society of Agronomy, Inc., Crop Science Society of America, Inc., and Soil Science Society of America, Inc. p. 393-411

Hanson, C.L., R.P. Morris, and J.R. Wight. 1983. Using precipitation to predict range herbage production in southwestern Idaho. *Journal of Range Management* 36:766-770

Hanson, C.L. 2001. Long-term precipitation database, Reynolds Creek Experimental Watershed, Idaho, United States. *Water Resources Research* 37:2831-2834

Hanson, C.L., D. Marks, and SS. Van Vactor. 2001. Long-term climate database, Reynolds Creek Experimental Watershed, Idaho, United States.

Hanson, C.L., J.R. Wight, and C.W. Johnson. 1994. Forage production, botanical composition, and ground cover on grazed and non-grazed plots. U.S. Department of Agriculture,

Agriculture Research Service, Northwest Watershed Research Center, Technical Report NWRC 94-1.

Hignett, C., and S. R. Evett. 2002. Neutron thermalization. *In:* J. H. Dane and G. C. Topp. Methods of Soil Analysis. Madison, WI, USA: Soil Science Society of America. p. 501-20

Hillel, D. 1998. Environmental soil physics. San Diego, CA, USA: Elsevier 771p.

Holecheck, J.L., R.D. Pieper, and C.H. Herbel. 2001. Range management: principles and practices. Upper Saddle River, NJ, USA: Prentice Hall 587p.

Ingram, J.A. 1974. Introductory Statistics. Menlo Park, CA, USA: Cummings Publishing Company 341 p.

Kiniry, J.R., J.R. Williams, P.W. Gassman, P. Debaeke. 1992. A general, process-oriented model for two competing plant species. *Transactions of the ASAE* 35:801-810

Kirkham, M.B. 2005. Principles of soil and plant water relations. Burlington, MA, USA: Elsevier, Inc. 500 p.

Miller, R.W. and D.T. Gardiner. 1998. Soils in our environment (eighth edition). Upper Saddle River, NJ, USA: Prentice Hall 736 p.

Oehlert, G.W. 2000. A first course in design and analysis of experiments. New York, NY, USA: W.H. Freeman and Company 659 p.

Saseendran, S.A., L.R. Ahuja, L. Ma, D. Timlin, C.O. Stockle, K.J. Boote, and G. Hoogenboom. 2008. Current water deficit stress simulations in selected agricultural system models, *In*: L.R. Ahuja, V.R. Reddy, S.A. Saseendran, and Q.Yu [EDS]. Response of Crops to Limited Water, understanding and modeling water stress effects on plant growth processes. Madison, WI, USA: American Society of Agronomy

Seyfried, M.S. 2003. Incorporation of remote sensing data in an upscaled soil water model. *In*: Y. Pachepsky, D.E. Radcliffe, H.M. Selim [EDS]. CRC Press, New York, NY, USA. Scaling Methods in Soil Physics. p. 309-346.

Seyfried, M.S., L.E. Grant, D. Marks, A. Winstral and J. McNamara. 2009. Simulated soil water storage effects on streamflow generation in a mountainous snowmelt environment, Idaho, USA. *Hydrological Processes*, 23: 858-873.

Seyfried, M.S. and M.D. Murdock. 2004. Measurement of soil water content with a 50-MHz soil dielectric sensor. *Soil Science Society of America Journal* 68:394-403

Seyfried, M. S., M. D. Murdock, C. L. Hanson, G. N. Flerchinger, and S. Van Vactor. 2001. Long-term soil water content database, Reynolds Creek Experimental Watershed, Idaho, United States. *Water Resources Research* 37:2847-51.

Sneva, F.A. and D.N. Hyder. 1962. Estimating herbage production on semiarid ranges in the intermountain region. *Journal of Range Management* 15:88-93

Tanner, C.B. and T.R. Sinclair. 1983. Efficient water use in crop production: research or re-search? *In*: H.M. Taylor, W.R. Jordan, and T.R. Sinclair [EDS]. Limitations to efficient water use in crop production. Madison, WI, USA: American Society of Agronomy, Inc., Crop Science Society of America, Inc., and Soil Science Society of America, Inc. p. 1-25

USDA, NRCS. 2010. The PLANTS database. Available at: http://plants.usda.gov. Accessed 17 November 2010.

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

Wight, J.R., C.L. Hanson, and D. Whitmer. 1984. Using weather records with a forage production model to forecast range forage production. *Journal of Range Management* 37:3-6

Wight, J.R., C.L. Hanson, and K.R. Cooley. 1986. Modeling evapotranspiration from sagebrush-grass-rangeland. *Journal of Range Management* 39:81-85

Wight, J.R. and C.L. Hanson. 1990. Crop coefficients for rangeland. *Journal of Range Management*. 43:482-485

Wight, J.R. and C.L. Hanson. 1991. Use of stochastically generated weather records with rangeland simulation models. *Journal of Range Management* 44:282-285

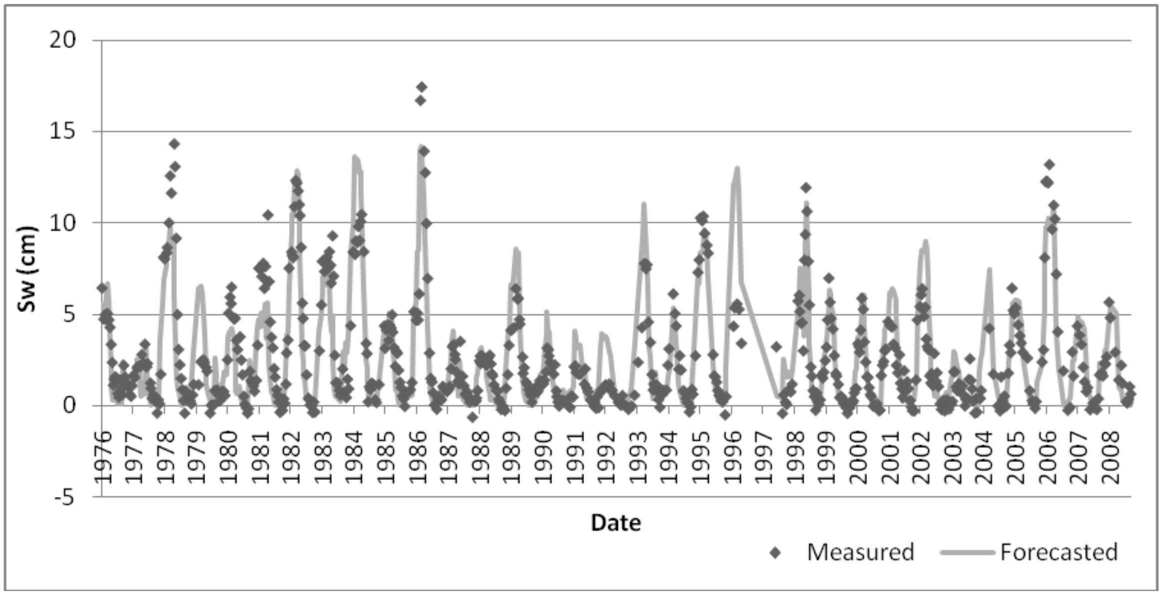

Figure 1: Simulated and measured total soil water (S_w) values at the Flats study site in Southwestern Idaho during the study period. Simulated values created by the Soil Ecohydrology Model reflect increases and decreases in measured S_w values.

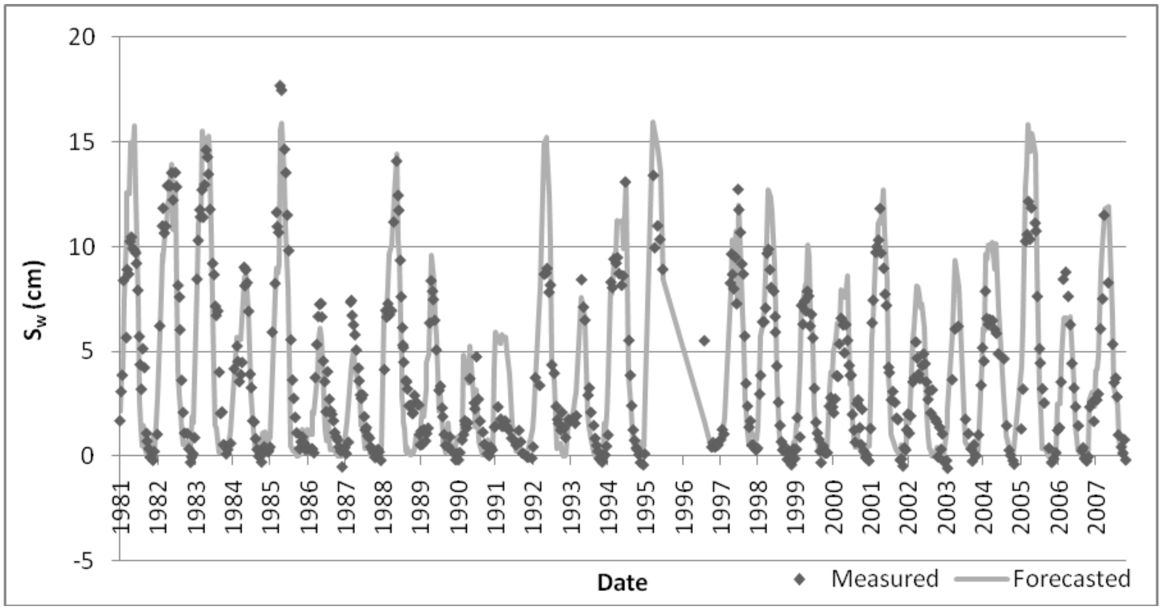

Figure 2: Simulated and measured total soil water (S_w) values at the Nancy's Gulch study site in southwestern Idaho during the study period. Simulated values created by the Soil Ecohydrology Model reflect increases and decreases in measured S_w values.

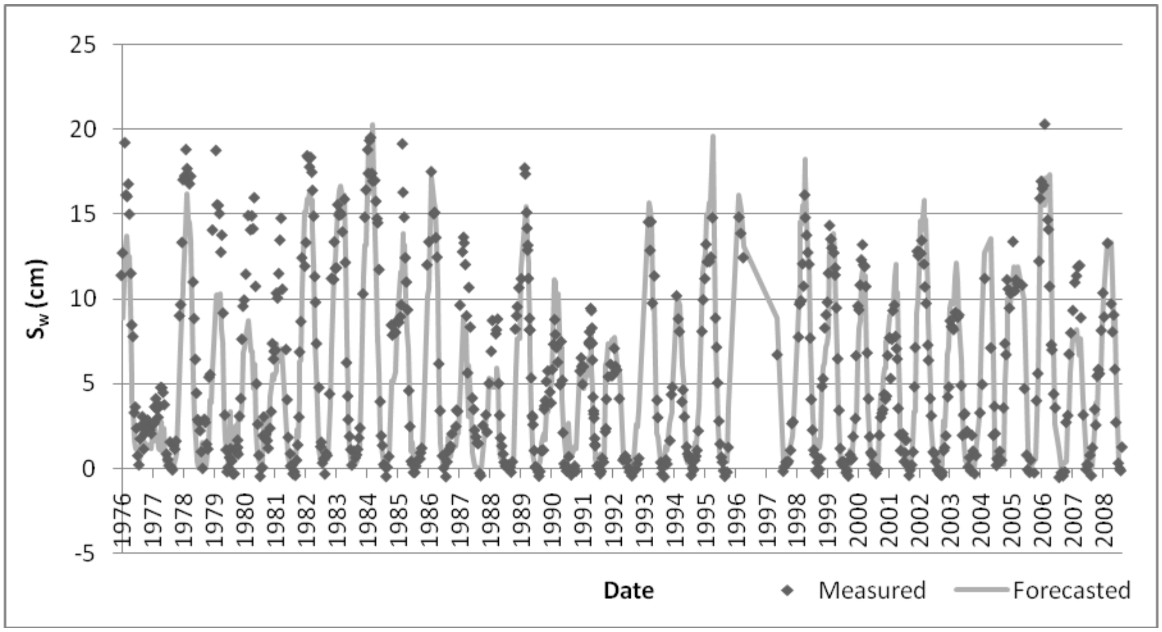

Figure 3: Simulated and measured total soil water (S_w) values at the Lower Sheep Creek study site in southwestern Idaho during the study period. Simulated S_w values created by the Soil Ecohydrology Model reflect increases and decreases in measured S_w values.

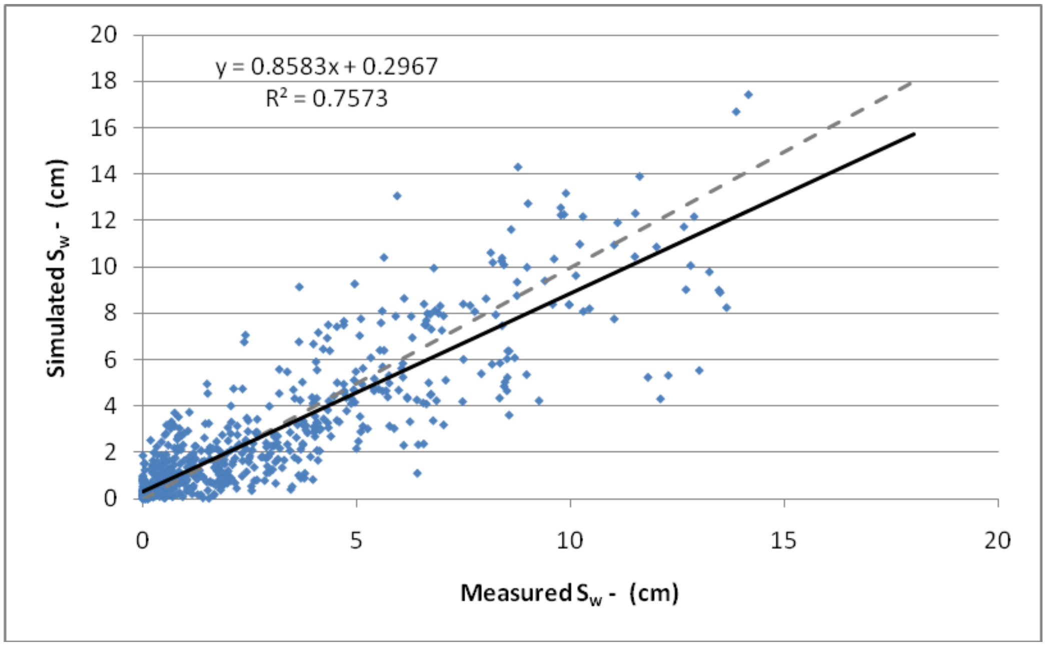

Figure 4: Simulated and measured total soil water (S_w) values at the Flats study site in southwestern Idaho during the study period, 1976-2008. Simulated values from the Soil Ecohydrology Model and those measured with a soil moisture meter are compared. Values represent total soil water (cm) for a soil profile and are calculated to a depth of 120 cm. The black regression line represents the regression equation. The dotted gray regression line represents a one to one regression equation.

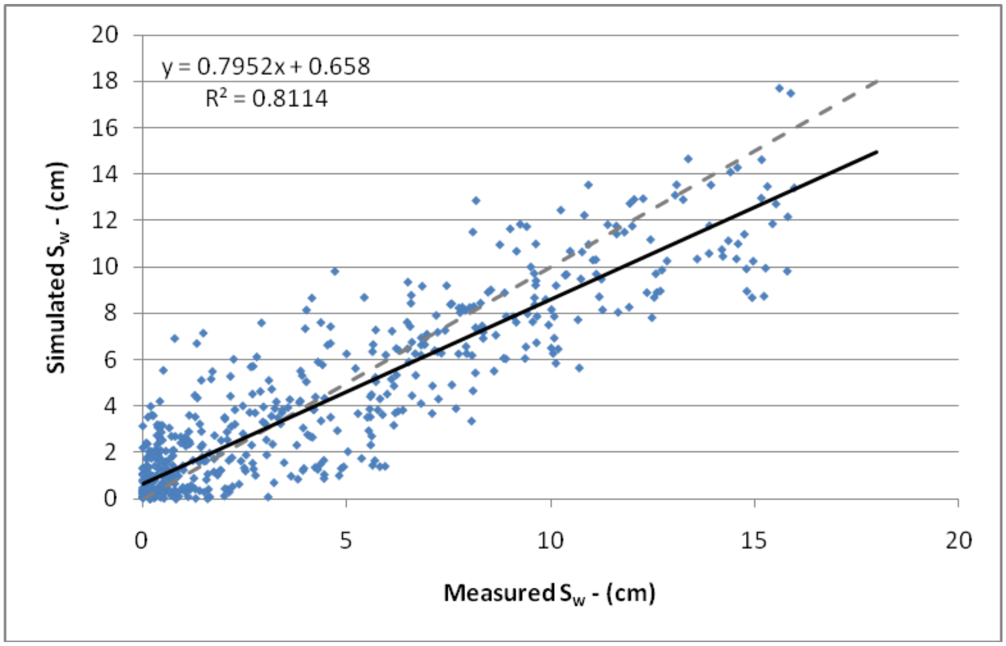

Figure 5: Simulated and measured total soil water (S_w) at the Nancy's Gulch study site in southwestern Idaho during the study period, 1976-2008. Simulated values from the Soil Ecohydrology Model and those measured with a soil moisture meter are compared. Values represent total soil water (cm) for a soil profile and are calculated to a depth of 120 cm. The black regression line represents the regression equation. The dotted gray regression line represents a one to one regression equation.

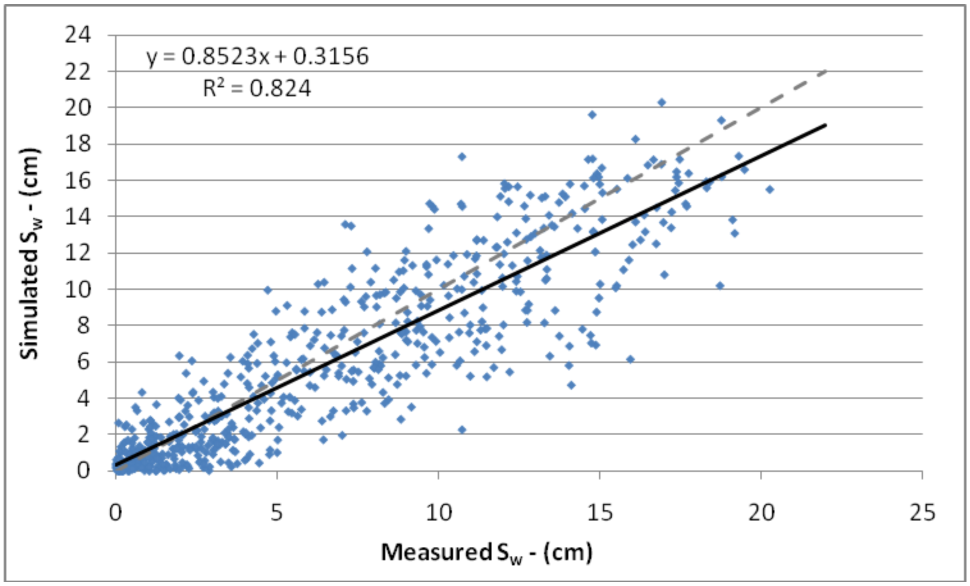

Figure 6: Simulated and measured S_w at the Lower Sheep Creek study site in southwestern Idaho during the study period, 1976-2008. Simulated values from the Soil Ecohydrology Model and those measured with a soil moisture meter are compared. Values represent total soil water (cm) for a soil profile and are calculated to a depth of 120 cm. The black regression line represents the regression equation. The dotted gray regression line represents a one to one regression equation.

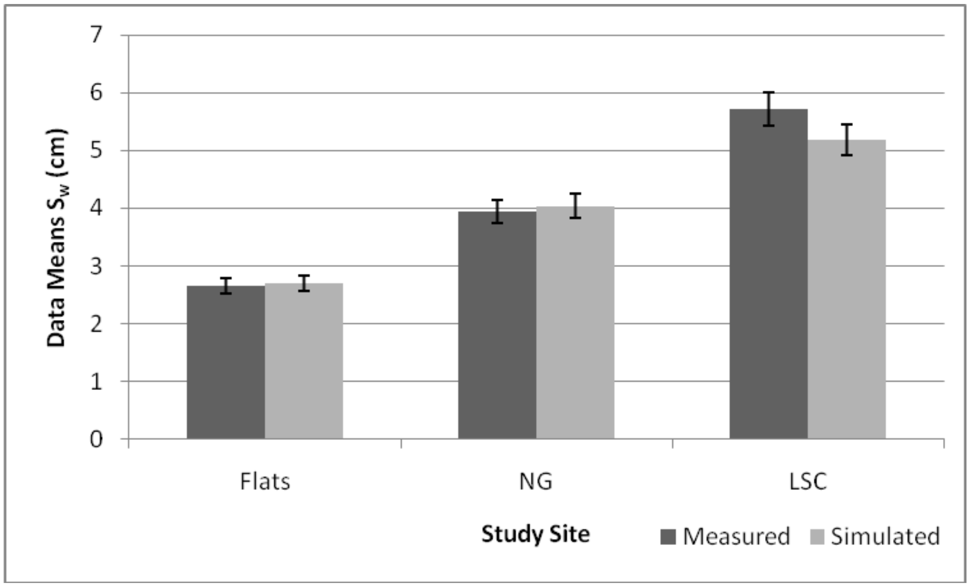

Figure 7: Data means for the Flats, Nancy's Gulch (NG) and Lower Sheep Creek (LSC) study sites in southwestern Idaho. Simulated values were created using the Soil Ecohydrology Model and measured values were collected with a neutron moisture meter. Values represent total soil water (cm) for a soil profile and are calculated to a depth of 120 cm.

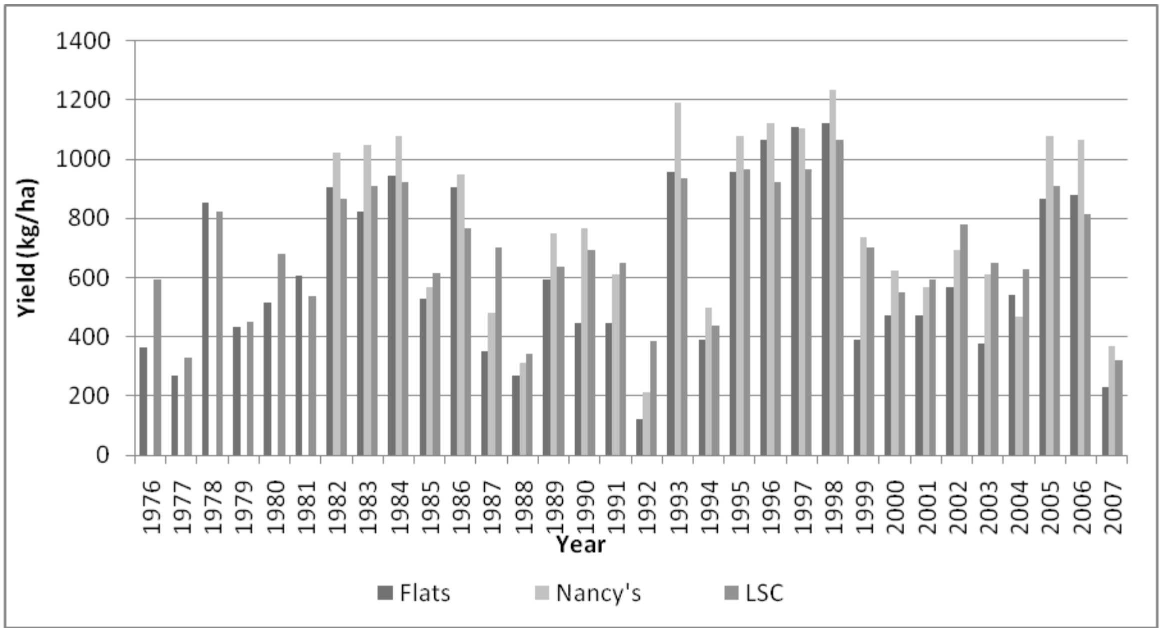

Figure 8: Forecasted yield at the Flats, Nancy's Gulch (Nancy's) and Lower Sheep Creek (LSC) based on site appropriate Ecological Site Descriptions and the Soil Ecohydrology Model yield index. Yield forecasts reflect annual increases and decreases in precipitation.

Table 1: Summary of analyses at each sampling and simulated depth. The summary reflects analyses done between measured and simulated soil moisture at each depth at the three study sites in southwestern Idaho.

15 centimeters	**Flats**	**Nancy's Gulch**	**Lower Sheep**
Regression line	y = 0.7781x + 0.0263	y = 1.1092x + 0.0237	y = 0.8008x + 0.0388
R-squared	0.615	0.726	0.663
Pearson's Corr.	0.784	0.852	0.814
Nash-Sutcliffe	0.520	0.329	0.575
30 centimeters			
Regression line	y = 1.0029x + 0.0015	y = 0.9784x - 0.007	y = 0.8697x - 0.0012
R-squared	0.694	0.810	0.724
Pearson's Corr.	0.833	0.900	0.851
Nash-Sutcliffe	0.554	0.759	0.673
60 centimeters			
Regression line	y = 0.8235x + 0.0005	y = 0.6749x - 0.0012	y = 1.3136x + 0.0074
R-squared	0.590	0.535	0.650
Pearson's Corr.	0.768	0.731	0.789
Nash-Sutcliffe	0.492	0.429	0.506
90 centimeters			
Regression line	y = 0.7471x + 0.0059	y = 0.7791x + 0.0021	y = 0.7135x - 0.0034
R-squared	0.327	0.215	0.633
Pearson's Corr.	0.572	0.464	0.796
Nash-Sutcliffe	0.137	-1.298	0.537
S_w			
Regression line	y = 0.8583x + 0.2967	y = 0.7952x + 0.658	y = 0.8523x + 0.3156
R-squared	0.757	0.811	0.824
Pearson's Corr.	0.870	0.901	0.925
Nash-Sutcliffe	0.736	0.755	0.814

Table 2: Annual precipitation (mm) at the study sites during the study period and estimated yield values (kg/ha) based on site appropriate Ecological Site Descriptions. Mean annual precipitation, minimum, and maximum are included.

	Flats		**Nancy's Gulch**		**Lower Sheep**	
Year	**Precipitation** (mm)	**Yield** (kg/ha)	**Precipitation** (mm)	**Yield** (kg/ha)	**Precipitation** (mm)	**Yield** (kg/ha)
1976	177	303	-	-	265	575
1977	262	224	-	-	295	319
1978	274	706	-	-	343	799
1979	208	359	-	-	267	437
1980	295	426	-	-	387	660
1981	275	504	-	-	362	522
1982	266	751	368	888	453	841
1983	385	684	474	912	536	884
1984	252	785	327	937	420	894
1985	228	437	266	493	294	596
1986	222	751	264	826	309	745
1987	196	291	230	419	311	681
1988	160	224	229	271	274	330
1989	156	493	193	653	201	618
1990	213	370	301	666	321	671
1991	201	370	255	530	304	628
1992	148	101	183	185	223	373
1993	265	796	326	1036	390	905
1994	210	325	243	432	294	426
1995	278	796	386	937	429	937
1996	385	885	529	974	569	894
1997	249	919	280	962	375	937
1998	388	930	486	1073	519	1033
1999	141	325	210	641	235	681
2000	222	392	291	542	306	532
2001	222	392	260	493	310	575
2002	132	471	204	604	243	756
2003	235	314	261	530	314	628
2004	203	448	278	407	320	607
2005	343	717	415	937	480	884
2006	218	729	315	925	354	788
2007	168	191	235	321	239	309
Mean	237	513	300	677	342	671
Minimum	132	101	183	185	201	309
Maximum	388	930	529	1073	569	1033

Chapter 2

The Indirect Measurement of Leaf Area Index in Sagebrush Steppe Rangelands

Julie Finzel[2]

ABSTRACT

Leaf area index (LAI) is defined as the one-sided area of leaves above a unit area of ground and is a critical measurement for the study of many biogeochemical cycles in ecosystems. Direct measurement of LAI requires the destructive collection of a representative sample of the vegetation being studied, but direct measurement techniques can be time-consuming and labor-intensive. Indirect methods for estimating LAI including point-intercept sampling, the Accupar ceptometer or lightbar (Decagon Devices, Pullman, WA), hemispherical photography and more were reviewed. The lightbar was evaluated for use in sagebrush steppe communities measuring LAI. Lightbar and point-intercept LAI data were collected at six sites in sagebrush steppe communities and the values were compared. The lightbar LAI values were consistently greater than point-intercept LAI values. The higher LAI values were attributed to the large woody component in shrubs. Using the methods presented in this study, the lightbar proved to be an unreliable method of measuring LAI in sagebrush steppe communities.

INTRODUCTION

Leaf area index (LAI) is defined as the one-sided area of leaves above a unit area of ground (Kirkham, 2005) and is related to plant production rate and plant-atmosphere gas exchanges (Kirkham, 2005; Larcher, 2003). The leaf is the primary organ on vascular plants that absorbs sunlight energy for conversion to kilocalories, absorbs carbon dioxide from the atmosphere and releases oxygen and water into the atmosphere (Barbour, 1999). The leaf is the location of many of the plant's most critical processes and the measurement of LAI is critical for the study

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[2] Mark Seyfried, Mark Weltz, Mari-Vaughn Johnson, and Jim Kiniry are additional contributing authors

of many biogeochemical cycles in ecosystems (Breda, 2003). It is also an essential input parameter in many process-based plant production models (Jonckheere et al., 2004).

The direct measurement of LAI requires the destructive collection of a representative sample of the plant(s) being studied. The individual leaves of each sample must be measured to determine the area of that sample. The most common method used to measure the area of leaves today is a planimeter. The planimeters most often used to measure LAI are automated devices equipped with a transparent conveyor belt that draws leaves into the machine where they are automatically measured and the sum of the area of all the leaves fed into the device is output on a small led screen. Before the development of the planimeter, measurements were taken by hand with leaves often being outlined onto square paper, with squares of known size, or photographed for future measurement (Evans, 1972).

Typically, a combination of the above described planimetric method and a gravimetric method are used to determine the LAI of a large sample of collected leaves. Sub-samples of the total leaves collected are weighed and then run through the planimeter to determine LAI. The remainder of the sample of leaves is then weighed and the previously established ratio of leaf weight to LAI is applied to determine LAI for the total sample (Breda, 2003; Jonckheere et al., 2004). In some cases, leaf area ratios (LAR) have been developed for specific species allowing the calculation of LAI based on the weight of a sample and plant growth stage (Weltz et al., 1992). During rapid plant growth LAI can change quickly, requiring frequent sampling to track change. The methods described above are time-consuming and destructive and repeated measurements cannot be made at the same location or on the same plant, limiting the usefulness and feasibility of the method.

Indirect methods of measuring LAI have been developed that require little or no destructive sampling. One well-established method developed and introduced by Levy and

Madden (1933), is point-intercept sampling, also called point quadrat and point/pin sampling. The point-intercept method was developed for use measuring vegetation dynamics in grasslands, but has been used extensively in many types of rangeland vegetation and is suited for use in any vegetation under 1.5 m tall (Levy and Madden, 1933; Coulloudon et al, 1996; Clark and Seyfried, 2001). There is considerable debate in the literature on the merits of using vertical point-frames or angled point-frames. Some researchers have found that angled or inclined point-frames are more precise and accurate than vertical point-frames (Wilson, 1959 and 1960) while others have found that the advantage of inclined versus vertical point-frames varies throughout the growing season (Drew, 1944). Clark and Seyfried (2001), working at Reynolds Creek Experimental Watershed in southwestern Idaho, tested inclined and vertical point-frames for accuracy and determined that point-intercept sampling using vertical point-frames is a valid method for estimating LAI in sagebrush. Goodall (1952) reviewed the point-intercept method and concluded that the point-intercept method is “one of the most trustworthy methods available”.

The point-intercept method uses either a pin sharpened to a point or a laser to create a point for which intercept can be accurately assessed. The point of the pin or the center of the laser is considered to be an intercept point, and when the intercept point hits vegetation it is called a “hit”, and each hit is recorded based on the objectives and protocol of the experiment. Typically, this includes recording each hit through the canopy of shrub, grass, or forb, down to the ground. The pins are mounted in a frame that holds them steady as they are lowered through vegetation. Lasers can also be mounted in a frame (Figure 9) with the laser beam directed vertically downward through the canopy (VanAmburg et al., 2005). As each hit is read, the data collector follows the laser visually through the vegetation and moves vegetation aside when necessary. The point-intercept method also provides data on percent cover and percent bare ground. Point-intercept can be used over a greater area then direct, destructive measurement of LAI, however it is still time and labor intensive because of the time associated with proper set-up of the point frame and the lowering of the pin, if pins are used instead of lasers. Lasers increase point-intercept sampling efficiency, but the method is still rather time-consuming because of the number of sampling points required to obtain a sufficient sample size (Goodall, 1952).

Other indirect LAI measurement methods include gap-fraction analysis using radiation measurement and hemispherical photography; it should be noted that if no corrections are made to remove branches and stems from indirect LAI measurements, Plant Area Index (Breda, 2003; Jonckheere et al., 2004) is a more appropriate term. A gap-fraction is defined as the fraction of background seen or measured; this can be from a viewpoint either above or below the vegetation (Baret et al., 2010). Gap-fraction analysis using radiation measurement can be split into two categories, those that require the use of the Beer-Lambert extinction law, and those that do not. The Beer-Lambert extinction law is expressed as:

$$I_z = I_o e^{-klai} \qquad \text{(Equation 1)}$$

where I_z is the intensity of radiation at a certain depth from the top of the canopy, I_o is the radiation incident at the top of the canopy, k is the extinction coefficient and LAI is the estimated leaf area index above the level of I_z per unit area of ground (Breda, 2003; Larcher, 2003). Two instruments that measure incident photosynthetically active radiation (PAR; 400-700 nm) and require the use of the Beer-Lambert extinction law to calculate LAI are the SunScan (Delta-T Devices Ltd, Cambridge, UK) and the Accupar ceptometer or lightbar (Decagon Devices, Pullman, WA, USA). The SunScan uses 64 linear sensors to measure PAR and can be used above and below the canopy. The lightbar uses 80 linear sensors to measure PAR and can also be used above and below the canopy. Both the SunScan and the lightbar are available with an optional external sensor that measures PAR above the canopy at the same time that measurements of PAR below the canopy are being taken. The SunScan and the lightbar are designed to be used with crops; a secondary suggested use for the lightbar is in forest canopies.

The Plant Canopy Analyzer, LAI-2000 (Li-Cor, Lincoln, Nebraska, USA) and the DEMON instrument (CSIRO, Canberra, Australia) do not require the use of the Beer-Lambert extinction law. The LAI-2000 has been used with crops and in coniferous and deciduous forests. It takes light measurements through a fish-eye sensor that measures in five angular bands and makes LAI estimates following each measurement (Breda, 2003; Jonckheere et al., 2004). The LAI-2000 does not require data processing post-collection, but it can only be used in diffuse light, for example a cloudy day or at sunrise or sunset. The DEMON instrument works like point-intercept sampling, except that the direct beam of the sun replaces the needle. The DEMON, though it was designed for forest use, has also been used in crops. When measurements are being taken the instrument must be held facing the sun. Multiple measurements must be taken to account for the angle of the sun at different times of the day; at least three in one day (Breda, 2003; Jonckheere et al., 2004).

Hemispherical photography, sometimes known as fish-eye photography, captures an image of vegetation and stores it for further processing and analysis. This method of vegetation analysis has been in use for over 35 years (Jonckheere et al., 2004), though it had not gained widespread popularity due to the time required to process images in the lab. With the forward strides that have been made through research and development in computers, software, and digital cameras there has been renewed interest in the method due to the technological advances that have reduced the amount of lab time required. A fish-eye lens is not required for proper image capture; a standard high resolution digital camera is sufficient (above 5 mega-pixels). HemiView (Delta-T Devices Ltd, Cambridge, UK), WinSCANOPY (Regent Instruments Inc., Quebec, Canada), and VegMeasure (Booth, 2005; Johnson, 2003; Louhiachi, 2001) are just a few of the software packages available today. It should be noted that the photo analysis software quantifies photos based on color, so the index produced is best referred to as a Green Area Index (Breda, 2003; Jonckheere, 2004)as opposed to LAI, as green plant parts that are not leaves will be counted in addition to leaves. A related software package, called GeoAlbum, highlights the importance of properly marking and saving digital photos so that the location, time, date and any other important information is attached to the photo; this also facilitates revisiting of photopoints when necessary.

This experiment involved the collection of LAI data as input criteria for the Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model (Kiniry et al, 1992). Two methods of indirect LAI measurement were examined: point-intercept sampling using a laser point frame and the lightbar. Point-intercept was selected because the method is considered a reliable estimate of LAI. The lightbar was examined because it has been used extensively in conjunction with the ALMANAC model and, of the methods described, the light bar is a promising alternative to the somewhat time-consuming point-intercept method because it is easy to use, relatively inexpensive, rapid and not destructive. The lightbar has not however, been evaluated in sagebrush-steppe vegetation. The objective of this research was to evaluate the application of the light bar for LAI measurement in sagebrush-steppe vegetation as an alternative to the point-intercept method.

This study was conducted over about a two year time span, with preparatory work beginning in the fall of 2008 and the last data collection completed in the early summer of 2010. Data were collected at six sagebrush steppe sites, three in Idaho and three in California, representing a wide range of vegetative conditions within the sagebrush steppe. The Idaho sites were located on Reynolds Creek Experimental Watershed in the Owyhee Mountains of southwestern Idaho. The California sites were located on Marble Creek, a grazing allotment managed by the BLM, just south of Benton, California at the base of the western side of the White Mountains. All sites were grazed at varying times of year throughout the study period.

METHODS

Site Description

The three California sites were at about the same elevation, 1850 m (6,100 ft), were laid out parallel to the north-south trend of the White Mountains and were spaced about 1 km apart. Mean annual precipitation at all California sites was 190mm (7.5 in); mean annual temperature was not available. Wyoming Big Sagebrush (*Artemisia tridentata* Nutt. ssp *wyomingensis* Beetle & Young) was a dominant component of the vegetation at all three sites. At the southernmost site, CA-south, Nevada Ephedra (*Ephedra nevadensis* S. Watson) was also dominant. Soil at CA-south was mapped as Ulymeyer-Rovana complex (5-15% slopes) classified as a sandy-skeletal, mixed, mesic Xeric Torriorthent with a parent material of alluvium derived from granite. At CA-middle Antelope Bitterbrush (*Purshia tridentata* [Pursh] DC) was co-dominant. Soil at CA-Middle was mapped as Bairs boulder loamy coarse sand (5-15% slopes) and classified as loamy-skeletal, mixed mesic Xeric Haplargids with a parent material of alluvium derived from granite. At CA-north, Nevada Ephedra was common with some Antelope Bitterbrush . Soil at this site was mapped as a Warrior very gravelly sandy loam (5-15% slopes), classified as loamy-skeletal, mixed (calcerous), mesic Xeric Torriothents with a parent material of alluvium derived from mixed material.

The three sites in Idaho, range from 1200 to 1600 m in elevation, represent differing climatic conditions and vegetative communities. At an elevation of 1190m (4,000 feet), ID-

Flats, had a mean annual precipitation of 240mm (23.5 inches) and a mean annual temperature of 9°C (23°F). The soil at ID-Flats was mapped as a Hardtrigger-Enko complex (2 – 15% slopes) with a parent material of volcanic ash and loamy alluvium. Dominant species were Wyoming Big Sagebrush, Shadscale Saltbush (*Atriplex confertifolia* [Torr. & Frem.] S. Watson), Bottlebrush Squirreltail (*Elymus elymoides* [Raf.] Swezey), and Sandberg Bluegrass (*Poa secunda* J. Presl). The ID-Nancy's Gulch (NG) study site, was at an elevation of 1400m (4,590 feet) and had a mean annual precipitation of 300mm (30 inches) and a mean annual temperature of 9°C (23°F). ID-NG soil was mapped as the Arbidge-Owsel-Gariper complex (1 – 15% slopes) with a parent material of volcanic ash, mixed alluvium, or loess. Vegetation at ID-NG was characterized by Wyoming Big Sagebrush, Bluebunch Wheatgrass *(Pseuodroegneria spicata* Pursh), Bottlebrush Squirreltail, and Sandberg Bluegrass as the dominant species. The ID-Lower Sheep Creek (LSC) study site in Idaho was at the highest elevation among the Idaho sites at 1627m (5,340 feet,) with a mean annual precipitation of 340mm (34 inches) and a mean annual temperature of 8°C (22°F) during the study period. The soil was mapped as a Vitale-Itca-Rubble land complex (2 - 60% slopes) with a parent material of Tephra, alluvium, or colluvium over bedrock. Dominant species at ID-LSC were Low Sagebrush (*Artemisia arbuscula* Nutt.), Lupine (*Lupinus* L. sp.), Milkvetch (*Astragalus* L. sp.) and Sandberg Bluegrass.

Experimental Layout

Four transects, each 50 meters long, were installed at each site. Quadrats were established on the south side of the transects, offset by 5 m, beginning at 3 m and continuing every 5 m, for a total of 10 quadrats. Forty 0.5 m by 1 m quadrats were established at each site, for a total of 120 quadrats in Idaho and 120 quadrats in California (Figure 10). Data collection protocol for a related project called for each quadrat to be clipped to the ground at the end of the growing season. To prevent clipping of the same area twice, the quadrats were moved to the north side of each transect for the second year of the study. The offset and all other quadrat placement criteria were repeated on the north side of each transect.

Measurement of Leaf Area Index

Point-intercept (PI) data were collected using the laser point-frame (LPF) within each quadrat at measurements of 10, 20, 30, and 40 cm along the 50 cm side of the quadrat. The LPF was designed in a “T” and three legs were used for support (Figure 9); the legs on the LPF were always placed outside the quadrat. The lasers were mounted in the long portion of the “T” and spaced 10 cm apart in a nadir orientation (VanAmburg et al., 2005; Seefeldt and Booth, 2006). The LPF was centered along the line of measurement within the quadrat and each hit was recorded from the top of the canopy down to the ground. Ground hits were considered to be anything that was laying directly on the soil, or was soil. Vegetation hits were recorded by species and noted as green or brown based on whether or not the vegetation was photosynthetically active. In 2009, PI data were collected at peak standing crop and in the fall to determine a baseline for each site. In 2010, PI data were collected in early to mid-spring and again at peak standing crop to establish a growth curve for each site. All quadrats were sampled at each site every time data were collected. LAI calculations from PI data were made by counting the number of green hits per sample area and dividing by the total number of sample points for the same sample area. For example there are 40 sample points per quadrat, if there were a total of 11 green hits in a quadrat 0.275 (i.e., 11/40 = 0.275) would be the LAI for that quadrat.

The lightbar was 80 cm long and therefore covered most of the length of the 1 m long quadrat. Lightbar measurements were taken parallel to the 1 m leg of the quadrat, near the center. Measurements were taken about every 10 cm across the width of the quadrat for a total of five measurements, which were averaged into a single value for each quadrat. This was repeated three times, resulting in three measured values for each quadrat. All 40 quadrats were not sampled at each site due to data collection time constraints and constraints associated with the optimum time-frame for collecting data using the lightbar (within 2 hours of solar noon is optimal and full sunlight is needed; cloudy days are not good days for collecting lightbar data). At peak standing crop in 2009, the quadrats along two of the transects at each site were sampled; 20 quadrats per site were sampled for a total of 120 quadrats. In the fall of 2009, this method was repeated, on the newly established quadrats on the north side of each transect. In the spring of 2010, lightbar data were collected twice, once in early to mid-spring and a second time at peak standing crop. Because of the large amount of interspace between shrubs at the study sites, sampling all 10 quadrats on two transects did not provide enough lightbar LAI measurements of shrubs. In the spring of 2010, quadrats were subjectively chosen to be sampled based on the presence of shrubs or parts of shrubs in the quadrat for a better comparison of the lightbar LAI data to PI LAI data and to better meet the objective of the study. Again, because of the large amount of bare ground at the study sites, it was not possible to sample 20 quadrats that had shrubs in them. As a result 9 to 15 quadrats were sampled at each site depending on the number of quadrats that had shrub cover. In one case, at ID-LSC during the early to mid-spring sampling in 2010, weather conditions were so cloudy only a few quadrats could be sampled with the lightbar. LAI calculations were made using Equation 1. The crop factor, “k”, was developed from 10 destructively sampled Wyoming Big Sagebrush shrubs of varying size and age collected from CA-North in the fall of 2008, at the inception of the study.

Data were analyzed using Systat 13 and Microsoft Excel. Regression analysis was done by plotting point-intercept LAI data against lightbar LAI data for each study site and each sampling period. An analysis of variance (ANOVA) was used to determine if there was a significant difference between point-intercept and lightbar LAI estimates. A Pearson's correlation was run between the lightbar LAI data and the point-intercept LAI data to determine how well the two datasets were correlated. Percent error values were calculated from the average absolute error and point-intercept LAI values.

RESULTS

Regression analysis results for the six sites and four sampling periods varied with R^2 values as low as 0.0004 and R^2 values as high as 0.6376. Regression equations calculated for each study site and each sampling period yielded slope values that ranged from -17 to almost zero to 4.2. These R^2 values and slopes indicate that lightbar LAI data were a poor fit to point-intercept LAI data. The graphs show significant data scatter around the regression lines (Figures 11 and 12).

The ANOVA results showed that the difference between the point-intercept and lightbar LAI estimates was significant with a p-value less than 0.05. The Pearson's correlation coefficient representing the correlation between the two datasets was 0.381, revealing a weak correlation between point-intercept and lightbar LAI data.

Percent error values showed that when point-intercept LAI values were zero, the percent error was 1210%. The percent error declined as point-intercept LAI values rose, indicating an inverse relationship. Point-intercept LAI values from 0.5 to 2.0 had the lowest percent error at 84%. Data means and standard deviation (Table 2) show higher variation overall in lightbar LAI estimates.

DISCUSSION

The lightbar LAI data correlate poorly with point-intercept LAI data and give variable readings. The lightbar tended to overestimate LAI. In sagebrush steppe communities where the mean LAI is typically below one, a difference of 0.1 is important; the lightbar overestimated LAI by 0.6 on average. The lightbar LAI estimate that best fits with a point-intercept LAI estimate was collected at peak standing crop in 2010 at RCEW-LSC. RCEW-LSC is the most productive of the six study sites and had the highest LAI values overall. The 2010 growing year was a productive year and the more accurate lightbar LAI measurements may be, in part, a reflection of higher LAI values in this year of study. This conclusion was supported by the percent error values that were calculated from the average absolute error and point-intercept LAI values.

Lightbar LAI data would be better represented if referred to as Plant Area Index (PAI) (Breda, 2003; Jonckheere et al., 2004) data because the lightbar does not distinguish between leaves and other, non-photosynthetic plant parts. In woody vegetation a significant portion of PAR is intercepted by woody plant material. It is possible that if methods were designed that adequately accounted for the woody plant material found in sagebrush steppe communities and other shrub communities the lightbar might be a suitable instrument for measuring LAI. Using the methods described in this paper, overestimation and poor correlation can be expected where variable densities of wood “appear” as LAI.

One of the goals of this study was to find indirect methods that could reduce the need for destructive LAI measurements. If destructive LAI measurements had been taken more frequently and in larger amounts it is possible that the extinction coefficient, “k”, in the Beer-Lambert calculations may have better accounted for the significant portion of woody material the lightbar interpreted as leaf area.

The lightbar is difficult to use with high precision on sloping ground because it was designed to be held level when taking measurements; accomplished using a bubble-level mounted on the instrument. This becomes difficult when working on uneven ground or on a slope. On a slope, if the lightbar is held parallel to the ground to take measurements from all vegetation present within the sampling area, it is not level and the angle of the sun and subsequent PAR is not consistent throughout the sampling period. If the lightbar is held level, vegetation is missed and an accurate measurement of site LAI is not collected. In areas with ditches and gullies the need to hold the lightbar level and the length of the lightbar can be challenging as it may not fit in the ditch or gully to measure the vegetation and it most likely will not fit *and* be level for accurate measurement of the vegetation.

CONCLUSIONS AND IMPLICATIONS

Measuring LAI in sagebrush steppe communities using the point-intercept method is valid and provides good estimates of LAI when sufficient sampling points are measured, but the method is time-consuming and labor-intensive. The use of the lightbar to measure LAI in sagebrush steppe vegetation produce inaccurate, imprecise data based on the methods used in this study. Little to no correlation was found between point-intercept and lightbar LAI data.

The importance of LAI data to understanding ecosystem processes and cycles will continue to motivate researchers to collect LAI data. A cost-effective, efficient and accurate method of LAI measurement would allow researchers to collect LAI data over greater spatial scales with manageable temporal and financial commitments. Hemispherical photography is a promising alternative that could provide accurate estimates of LAI efficiently. Continued research is needed to improve LAI measurement methods in conjunction with technological advances.

LITERATURE CITED

Barbour, M.G., J.H. Burk, W.D. Pitts, F.S. Gilliam, and M.W. Schwartz. 1999. Terrestrial plant ecology. Menlo Park, CA, USA: Benjamin/Cummings an imprint of Addison Wesley Longman, Inc. 649 p.

Baret, F., B. de Solan, R. Lopez-Lozano, K. Ma, and M. Weiss. 2010. GAI estimates of row crops from downward looking digital photos taken perpendicular to rows at 57.5^{o} zenith angle: Theoretical considerations based on 3D architecture models and application to wheat crops. *Agricultural and Forest Meteorology* 150:1393-1401

Breda, N.J.J. 2003. Ground-based measurements of leaf area index: a review of methods, instruments and current controversies. *Journal of Experimental Botany* 54:2403-2417

Clark, P.E. and M.S. Seyfried. 2001. Point sampling for leaf area index in sagebrush steppe communities. *Journal of Range Management* 54:589-594

Coulloudon, B., K. Eshelman, J. Gianola, N. Habich, L. Hughes, C. Johnson, M. Pellant, P. Podborny, A. Rasmussen, B. Robles, P. Shaver, J. Spehar, and J. Willoughby. 1996. Sampling Vegetation Attributes: Bureau of Land Management TR 1734-4 172p.

Drew, W.B. 1944. Studies on the use of the point-quadrat method of botanical analysis of mixed pasture vegetation. *Journal of Agricultural Research* 69:289-297

Evans, G.C. 1972. The quantitative analysis of plant growth. Berkeley and Los Angeles, CA, USA: Blackwell Scientific Publications and the University of California Press. 734 p.

Goodall, D.W. 1952. Some considerations in the use of point-quadrats for analysis of vegetation. *Australian Journal of Scientific Research, Series B* 5:1-41

Ingram, J.A. 1974. Introductory Statistics. Menlo Park, CA, USA: Cummings Publishing Company 341 p.

Johnson, D.E., M. Vulfson, M. Louhaichi, and N.R. Harris. 2003. VegMeasure version 1.6 user's manual. Department of Rangeland Resources, Oregon State University, Corvallis, Oregon, USA

Jonckheere, I., S. Fleck, K. Nackaerts, B. Muys, P. Copping, M. Weiss, and F. Baret. 2004. Review of methods for in situ leaf area index determination part I. Theories, sensors, and hemispherical photography. *Agricultural and Forest Meteorology* 121:19-35.

Kiniry, J.R., J.R. Williams, P.W. Gassman, P. Debaeke. 1992. A general, process-oriented model for two competing plant species. *Transactions of the ASAE* 35:801-810

Kirkham, M.B. 2005. Principles of soil and plant water relations. Burlington, MA, USA: Elsevier, Inc. 500 p.

Larcher, W. 2003. Physiological Plant Ecology. Berlin, Germany: Springer-Verlag 531 p.

Levy, E.B. and E.A. Madden. 1933. The point method of pasture analysis. *New Zealand Journal of Agriculture* 46:267-79

Louhiachi, M., M.M. Borman, and D.E. Johnson. 2001. Spatially located platform and aerial photography for documentation of grazing impacts on wheat. *Geocarta* 16:63-68

Seefeldt, S.S. and D.T. Booth. 2006. Measuring plant cover in sagebrush steppe rangelands: a comparison of methods. *Environmental Management* 37:703-711

Seyfried, M. S., M. D. Murdock, C. L. Hanson, G. N. Flerchinger, and S. Van Vactor. 2001. Long-term soil water content database, Reynolds Creek Experimental Watershed, Idaho, United States. *Water Resources Research* 37: 2847-51.

VanAmburg, L.K., D.T. Booth, M.A. Weltz, and M.J. Trlica. 2005. A laser point frame to measure cover. *Rangeland Ecology and Management* 58:557-560

Weltz, M.A., W.H. Blackburn, and J.R. Simanton. 1992. Leaf area ratios for selected rangeland plant species. *Great Basin Naturalist* 52:237-244

Wilson, J.W. 1959. Analysis of the spatial distribution of foliage by two-dimensional point quadrats. *New Phytologist* 58:92-99

Figure 9: The laser point frame is supported by three adjustable height legs. The lasers are spaced 10 cm apart in the long portion of the “t” and point downward toward the ground.

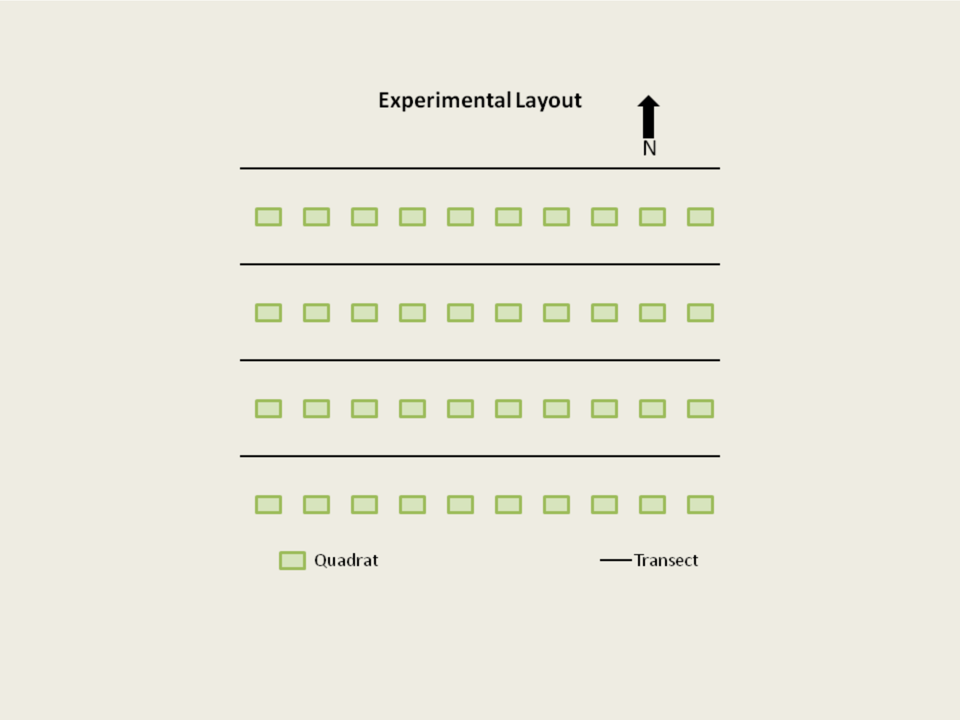

Figure 10: The experimental layout consisted of four 50 m transects 10 to 25 m apart with 10 quadrats per transect. Quadrats were spaced 5 m apart, offset from the transect 5 m and started at the 3 m measurement. In 2009, quadrats were placed on the south side of transects and in 2010, quadrats were placed on the north side of the transects.

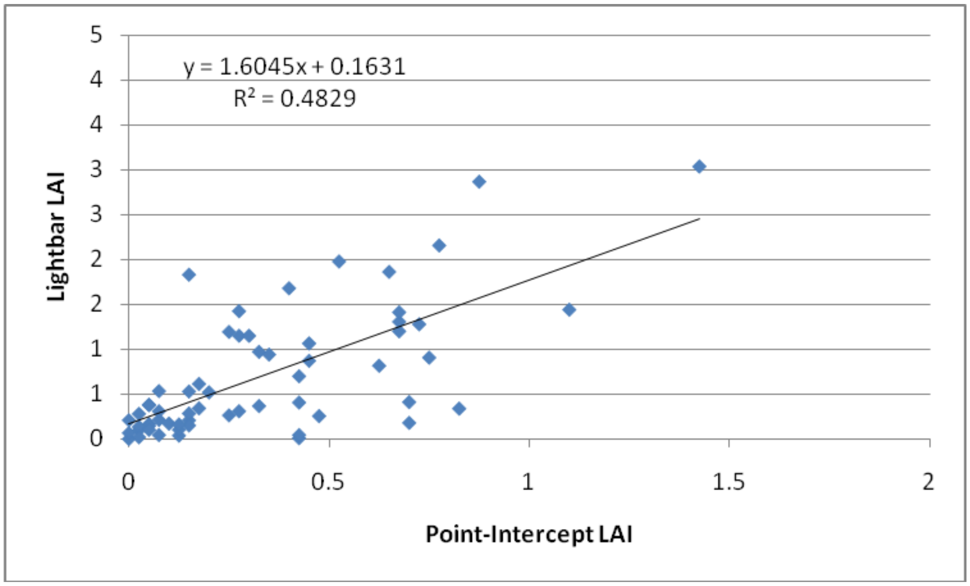

Figure11: Point-intercept LAI and lightbar LAI estimates from Idaho sites at peak standing crop 2009 are compared using a regression equation and the R^2 correlation.

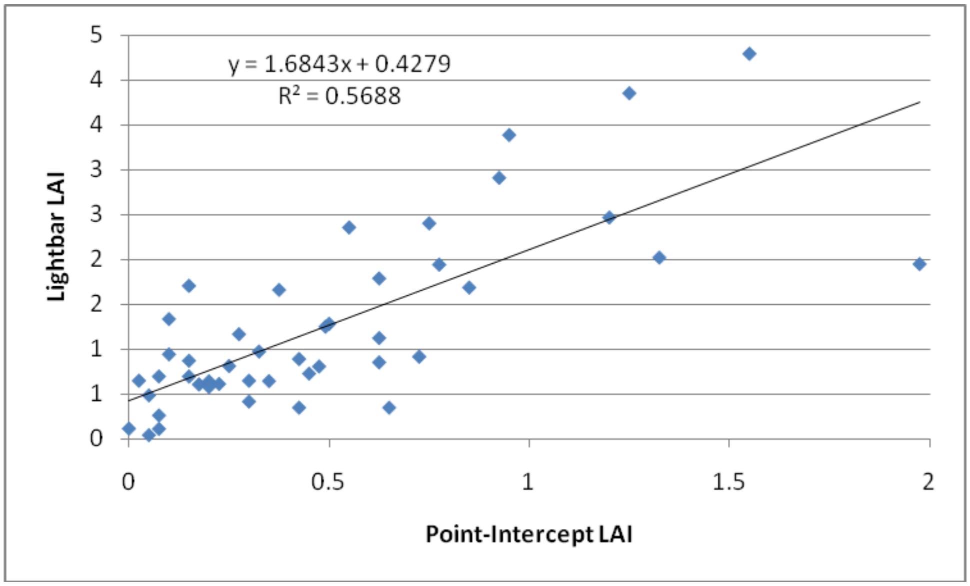

Figure12: Point-intercept LAI and lightbar LAI estimates from California sites at peak standing crop, 2010 are compared using a regression equation and the R^2 correlation.

Table 3: Lightbar (LB) and point-intercept (PI) means and standard deviations averaged over the 3 study sites in each state and calculated by sampling period.

	Sampling	LB Mean	LB StDev	PI Mean	PI StDev
California	Peak 2009	0.706	0.755	0.253	0.323
	Fall 2009	1.064	0.833	0.099	0.134
	Spring 2010	1.067	0.901	0.216	0.216
	Peak 2010	1.255	0.983	0.491	0.367
Idaho	Peak 2009	0.704	0.705	0.337	0.308
	Fall 2009	0.709	0.975	0.118	0.108
	Spring 2010	0.622	0.413	0.399	0.194
	Peak 2010	0.669	0.311	0.656	0.406

Chapter 3

Quantifying Key Vegetation Attributes in Sagebrush Steppe Rangelands

Julie Finzel[3]

ABSTRACT

Quantifying key vegetation attributes is critical for rangeland managers as they strive to understand ecosystem functions and meet management objectives. Quantifying key management objectives is also important for calibration and validating models that simulate ecosystem processes like evapotranspiration, plant water uptake, nutrient uptake, and plant growth. A model that forecasted plant growth would help ranchers and other land managers meet land management objectives. The objective of this study was to quantify key vegetation attributes in sagebrush steppe rangelands to provide calibration and validation criteria for vegetation production forecasting models and systems. Climate and soil moisture data were collected in addition to sampling vegetation for leaf area index, percent cover, standing biomass and vegetation yield. Results showed low standard error values for all datasets. The relationships between LAI and yield and percent cover and biomass were quantified. Results showed a strong correlation between LAI and yield, and a very weak relationship between percent cover and biomass. Vegetation attributes were successfully measured and described using the methods presented. Improvements and modifications to the methods are discussed as potential revisions to current calibration and validation criteria used in vegetation production forecasting systems.

INTRODUCTION

One of the main tools rangeland managers use to understand and quantify ecosystem function is the measurement of key vegetation attributes. Key vegetation attributes include, but are not

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[3] Mark Seyfried, Mark Weltz, and Karen Launchbaugh are additional contributing authors

limited to, percent cover, leaf area index (LAI), plant frequency, plant density, standing biomass, and yield or plant growth. Key vegetation attributes provide feedback on management objectives and actions and can direct future changes in management. Key vegetation attributes also serve as important calibration and validation criteria for rangeland models that simulate ecosystem processes like evapotranspiration, plant water uptake, nutrient uptake, and plant growth.

Drought is a naturally occurring meteorological phenomenon that is defined by the Society for Range Management as “prolonged dry weather, generally when precipitation is less than 75% of average annual amount (Holecheck, 2001).” The time span of a drought can be as short as a year, or it can be as long as 5 or more years (Holecheck, 2001). The longer a drought lasts, the more adversely and intensely the water supply and vegetation are affected. Drought affects everyone, from farmers and ranchers whose financial stability is threatened, to city dwellers, whose water use may be restricted to ensure the basic needs of all can be met. The ability of meteorologists to predict drought is limited (University of Nebraska, Lincoln, 2010), giving many land managers little time to prepare for a shortage of rainfall, and subsequent shortages of forage.

If livestock and land managers were able to plan for oncoming drought, they would be better equipped to strategically make decisions that would create additional forage resources, limit production costs and manage livestock assets. This study focused on quantifying key vegetation attributes to serve as calibration and validation criteria for vegetation production forecasting models as elements of a vegetation production forecasting system. Research occurred within sagebrush steppe rangelands where there are a wide range of vegetation types and growing environments. It is important to understand the range of these conditions to successfully simulate ecosystem processes in sagebrush steppe rangelands. Specific objectives included the collection of soil moisture measurements, climate data, and the following key vegetation attributes: percent cover by species, LAI, standing biomass, and plant growth. An additional objective of this study was to determine the relationship between LAI and yield and cover and biomass. This study was part of a larger project intended to investigate the effects of climate and soils on vegetation production in sagebrush-steppe rangelands.

This study was conducted over the course of about two years, beginning in fall 2008 with planning and preliminary data collection and ending in early summer 2010. Data were collected at six sagebrush steppe sites, three in Idaho and three in California, that represent a wide range of vegetative conditions within the sagebrush steppe. The Idaho sites were located on Reynolds Creek Experimental Watershed in the Owyhee Mountains of southwestern Idaho. The California sites were located on Marble Creek, a grazing allotment managed by the BLM and just south of Benton, California at the base of the western side of the White Mountains. All sites were actively grazed at varying times of year throughout the study period.

METHODS

Site Description

The three California sites were at about the same elevation, 1850 m (6,100 ft), ran parallel to the north-south trend of the White Mountains and were spaced about 1 km apart. Mean annual precipitation at all CA sites was 190mm (7.5 in); mean annual temperature was not available. Wyoming Big Sagebrush (*Artemisia tridentata* Nutt. ssp *wyomingensis* Beetle & Young) was a dominant component of the vegetation at all three sites. At the southernmost site, CA-south, Nevada Ephedra (*Ephedra nevadensis* S. Watson) was also dominant. Soil at CA-south was mapped as Ulymeyer-Rovana complex (5-15% slopes) classified as a sandy-skeletal, mixed, mesic Xeric Torriorthent with a parent material of alluvium derived from granite. At CA-middle Antelope Bitterbrush (*Purshia tridentata* [Pursh] DC) was co-dominant. Soil at CA-

Middle was mapped as Bairs boulder loamy coarse sand (5-15% slopes) and classified as loamy-skeletal, mixed mesic Xeric Haplargids with a parent material of alluvium derived from granite. At CA-north, Nevada Ephedra was common with some Antelope Bitterbrush . Soil there was mapped as a Warrior very gravelly sandy loam (5-15% slopes), classified as loamy-skeletal, mixed (calcerous), mesic Xeric Torriothents with a parent material of alluvium derived from mixed material.

The three sites in Idaho, range from 1200 to 1600 m in elevation, represent differing climatic conditions and vegetative communities. At an elevation of 1190m (4,000 feet), ID-Flats, had a mean annual precipitation of 240mm (23.5 inches) and a mean annual temperature of 9°C (23°F). The soil at ID-Flats was mapped as a Hardtrigger-Enko complex (2 – 15% slopes) with a parent material of volcanic ash and loamy alluvium. Dominant species were Wyoming Big Sagebrush, Shadscale Saltbush (*Atriplex confertifolia* [Torr. & Frem.] S. Watson), Bottlebrush Squirreltail (*Elymus elymoides* [Raf.] Swezey), and Sandberg Bluegrass (*Poa secunda* J. Presl). The ID-Nancy's Gulch (NG) study site, was at an elevation of 1400m (4,590 feet) and had a mean annual precipitation of 300mm (30 inches) and a mean annual temperature of 9°C (23°F). ID-NG soil was mapped as the Arbidge-Owsel-Gariper complex (1 – 15% slopes) with a parent material of volcanic ash, mixed alluvium, or loess. Vegetation at ID-NG was characterized by Wyoming Big Sagebrush, Bluebunch Wheatgrass *(Pseuodroegneria spicata* Pursh), Bottlebrush Squirreltail, and Sandberg Bluegrass as the dominant species. The ID-Lower Sheep Creek (LSC) study site in Idaho was at the highest elevation among the Idaho sites at 1627m (5,340 feet,) with a mean annual precipitation of 340mm (34 inches) and a mean annual temperature of 8°C (22°F) during the study period. The soil was mapped as a Vitale-Itca-Rubble land complex (2 - 60% slopes) with a parent material of Tephra, alluvium, or colluvium over bedrock. Dominant species at ID-LSC were Low Sagebrush (*Artemisia arbuscula* Nutt.), Lupine (*Lupinus* L. sp.), Milkvetch (*Astragalus* L. sp.) and Sandberg Bluegrass.

Experimental Layout

Four transects, each 50 meters long, were installed at each site (Figure 13). Quadrats were established on the south side of the transects, offset by 5 m, beginning at 3 m and continuing every 5 m, for a total of 10 quadrats. Forty 0.5 m by 1 m quadrats were established at each site, for a total of 120 quadrats in Idaho and 120 quadrats in California. Data collection protocol for a related project called for each quadrat to be clipped to the ground at the end of the growing season. To prevent double-sampling of any one area, the quadrats were moved to the north side of each transect for the second year of the study. The offset and all other quadrat placement criteria were repeated on the north side of each transect.

Soil Moisture Measurement and Climate Monitoring

A special emphasis was placed on soil moisture measurement and simulation due to the strong relationship between plant available water, water stress, and plant production (Hillel 1998; Larcher, 2003; Kirkham, 2005). Soil moisture sensors were installed at the six sites. The soil moisture sensors used were Stephen's Hydraprobe II (Portland, OR). The hydraprobe is a coaxial dielectric sensor that measures 22 soil attributes. Soil moisture probes were placed at depths of 5, 15, 30, 60, and 90 centimeters. A basic soil analysis was completed at each site to determine key soil attributes including type and texture. Soil pits were hand dug and soil moisture sensors were installed in undisturbed soil along a wall inside the soil pit wherever possible. In some cases, sensors were placed partially in the pit wall and soil was packed around them. Soil moisture data were recorded every hour; soil moisture data were still being monitored and recorded at all sites at the time of this writing.

The data loggers and precipitation gages utilized in California were manufactured by Campbell Scientific (Logan, UT). The precipitation gage used was a tipping bucket with a snowfall adapter. A tipping bucket rain gage has a funnel that directs precipitation into a bucket mechanism that tips. Each time the bucket tips, a switch is tripped and the amount of precipitation is by the number of times the switch is tripped. Tipping bucket rain gages were installed at CA-South and CA-North.

At CA-Middle a Natural Resources Conservation Service (NRCS) Soil Climate Analysis Network (SCAN) site was installed. NRCS SCAN sites monitor soil moisture and precipitation in addition to wind speed and direction, solar radiation, and outdoor temperature. SCAN sites utilize the same soil moisture sensors and place them at the similar depths as those used at the other five study sites. SCAN sites also utilize the same tipping bucket installed at CA-South and CA-North.

All ID sites were co-located with preexisting, long-term meteorological stations. Precipitation, wind direction and speed, solar radiation, and outdoor temperature were collected at all ID sites during the study period. For further information see Hanson (2001), Seyfried et al. (2001), and Slaughter et al. (2001).

Measurement of Leaf Area Index and Percent Cover

Two indirect methods of measuring LAI were used in this study; point-intercept and gap fraction analysis. Gap fraction analysis data and results were presented and discussed in chapter 2 of this thesis. Point-intercept sampling is a well-established method developed and introduced by Levy and Madden (1933); this method has also been called point quadrat and point/pin sampling. The point-intercept method was developed for use measuring vegetation dynamics in grasslands, but has been used extensively in many types of rangeland vegetation and is suited for use in any vegetation under 1.5 m tall (Levy and Madden, 1933; Coulloudon et al., 1996; Clark and Seyfried 2001). Point-intercept sampling provides data on leaf area index and percent cover. LAI is defined as the one-sided area of leaves above a unit area of ground (Kirkham, 2005) and is related to plant production rate and plant-atmosphere gas exchanges (Kirkham, 2005; Larcher, 2003). Properly designed point-intercept methods provide data that can be used to calculate the four types of percent cover: ground, canopy, foliar, and basal (Coulloudon et al., 1996; Elzinga et al., 2001). Percent cover is defined as “the vertical project of vegetation from the ground as viewed from above (Elzinga et al., 2001)”, this sometimes includes rocks, litter and cryptograms. Percent cover can be used to determine species composition and is important to site hydrology (Elzinga et al., 2001; Herrick et al., 2005). Percent cover is often related to biomass (Elzinga et al., 2001).

The point-intercept method uses either a pin, sharpened to a point for accurate readings, or a laser. The point of the pin or the center of the laser is considered to be an intercept point, and when the intercept point hits vegetation it is called a “hit”; each hit is recorded based on the objectives and protocol of the experiment. Typically this includes recording each hit through the canopy of shrub, grass, or forb, down to the ground. The pins are mounted in a frame that holds them steady as they are lowered through vegetation; the frame also serves to maintain the desired angle of sampling. The lasers are also mounted in a frame, but they are not lowered through vegetation (VanAmburg et al., 2005). As each hit is read, the data collector follows the laser visually through the vegetation and moves vegetation aside when necessary.

Point-intercept (PI) data were collected using the laser point-frame (LPF) within each quadrat at measurements of 10, 20, 30, and 40 cm along the 50 cm side of the quadrat. The LPF was designed in a “T” and three legs were used for support; the legs on the LPF were always placed outside the quadrat. The lasers were mounted in the long portion of the “T” and spaced

10 cm apart in a nadir orientation (VanAmburg et al., 2005; Seefeldt and Booth, 2006). The LPF was centered along the line of measurement within the quadrat and each hit was recorded from the top of the canopy down to the ground. Ground hits were considered to be anything that was laying directly on the soil, or was soil. Vegetation hits were recorded by species and noted as green or brown based on whether or not the vegetation was photosynthetically active. In 2009, PI data were collected at peak standing crop and in the fall to determine a baseline for each site. In 2010, PI data were collected in early to mid-spring and again at peak standing crop to establish a growth curve for each site. All quadrats were sampled at each site every time data were collected. LAI calculations from PI data were made by counting the number of green hits per sample area and dividing by the total number of sample points for the same sample area. For example there are 40 sample points per quadrat, if there were a total of 11 green hits in a quadrat 0.275 (i.e., 11/40 = 0.275) would be the LAI for that quadrat.

Dimension Analysis

Estimates of standing biomass were calculated using dimension analysis and allometric relationships according to the methods developed and described by Rittenhouse and Sneva (1977). In this study, standing biomass was defined as total live standing vegetation, including new and old growth. Standing biomass provides data related to plant succession, fire fuel loads, and wildlife habitat (Cleary et al., 2007; Rittenhouse and Sneva, 1977).

The widest portion of the shrub canopy was measured, and a second measurement of width was taken directly perpendicular to the first measurement. Plant height was measured from the bottom of live canopy to the top of the live canopy. The equations and relationships developed by Rittenhouse and Sneva (1977) were used to calculate general estimates for standing biomass of all shrubs. No destructive samples were taken to develop independent allometric relationships.

Vegetation Sampling

Plant growth, or annual aboveground net primary production, is rarely measured and almost never forecasted by ranch or rangeland managers even though it is a critical component of a rational range management system. Plant growth data provide important information on available forage for livestock and wildlife, help define successional state, and are a good way to track potential vegetation change.

To determine plant growth at the study sites, each quadrat was clipped to the ground. Only vegetation inside the quadrat was collected, but the vegetation did not have to be rooted in the quadrat to be collected. Vegetation was clipped by species. Grasses and forbs were clipped as close to the ground as possible and all current year growth was removed and placed in a paper bag. Any shrub plant parts present in a quadrat were collected, including the main stem.

Determining new growth on grasses and forbs was straightforward and could be done rapidly in the field as part of the collection process. Determining and separating new growth on shrubs was not as straightforward. New growth on shrubs was considered to be any stem that was green and flexible, compared to mature stems from the rest of the plant, and all deciduous leaves that are replaced annually.

To increase efficiency and uniformity the methods used in 2009 were modified slightly for the 2010 growing season. In 2010, all grasses and forbs were still clipped as close to the ground as possible and collected by species; the protocol did not change for grasses and forbs. A subsample technique using a representative weight unit was used to determine new growth on shrubs. A representative portion of the shrub was selected that was in an approximate circle around the circumference of the author's hand (about 6 cm with an area of 0.28 m^2). The number of circles (units) per plant was counted and recorded, but only the representative portion of the shrub was collected. Vegetation within the representative portion of the shrub was clipped from the top of the live canopy to the bottom of the live canopy. New growth was separated from the collected portion of the shrub and multiplied by the number of units counted within the plant. This method was used on all shrubs with two or more units and is an adaptation of two similar methods described by Herrick (2005) and Fernandez (1991).

Vegetation was dried in a constant temperature oven, bags open, at 65°C for 48 hours. After 48 hours, the vegetation was removed from the oven and weighed. Vegetation was not saved or stored for any further processing.

Data were analyzed using Systat 13 and Microsoft Excel. Pearson's correlations and regression equations were calculated to determine potential correlations and relationships between datasets. Standard error and confidence intervals were calculated to define precision within datasets.

RESULTS

LAI values generally reflected seasonal variation, with the highest observed LAI at peak standing crop (Figure 14); an anomaly was seen at ID-Nancy's Gulch where LAI dropped from spring 2010 to peak 2010, which may have resulted from spring grazing on the site. Standard error values were low with all values less than 0.04. Percent vegetation cover varied over the sampling periods, but did not reflect seasonal change (Figure 15). Standard error values were low with all values less than 0.32. Standing biomass varied between years, with lower biomass levels observed in 2010 than in 2009 (Figure 16). It is not clear why cover values did not follow patterns in biomass. It is possible that the data were reflecting on site variation that occurred from the south side of the transect to the north side. This may be especially true at CA-South, where significant standing dead vegetation seemed to occur within the quadrats and sample area of the south side of Transect 1. There was less standing dead vegetation on the north side of Transect 1 at CA-South. Yield values increased from 2009 to 2010 (Figure 17). It is hypothesized that the improved growing conditions were due to consistent rainfall from March until May or June, depending on location.

The relationship between LAI and yield was examined using Pearson's correlation and regression analysis (Figures 18 and 19). The correlation coefficient was 0.881, showing a strong correlation between the LAI and yield datasets. Regression analysis revealed a moderately strong relationship between LAI and yield with an R^2 value of 0.776.

The relationship between LAI and percent cover was examined using Pearson's correlation and regression analysis (Figures 20 and 21). The correlation coefficient was 0.927 indicating a strong correlation between the LAI and percent cover datasets. Regression analysis revealed a somewhat strong relationship between LAI and cover with an R^2 of 0.859.

The relationship between percent cover and standing biomass was examined using Pearson's correlation and regression analysis (Figures 22 and 23). Pearson's correlation coefficient was -0.193 reflecting a weak inverse relationship between percent cover and biomass. Regression analysis revealed an extremely weak relationship between percent cover and standing biomass estimates with an R^2 of 0.037.

DISCUSSION

The soil moisture sensor and climate instruments collected the basic data needed to calibrate a model to each site and simulate soil moisture or forecast yield. The instruments are expensive though and the cost would most likely be prohibitive for a rancher or other land manager interested in using a vegetation production forecasting system. The evaluation of more affordable, high-quality instruments is needed to make a vegetation production forecasting system economically available to a wide range of users. Decagon (Pullman, WA) makes soil moisture sensors that can be installed with a data logger at 4 depths for less than twelve hundred dollars. Davis instruments (Hayward, CA) manufactures a climate monitoring system that can be installed with a data logger for about thirteen hundred dollars. While these systems are still expensive, they are much more affordable than the systems used in this study, which cost about five thousand dollars for just the soil moisture sensor system.

The experimental layout was scientifically rigorous and provided a large number of sampling points, but the 0.5 m^2 quadrat area may not have been large enough at the CA sites due to the large bare interspaces between shrubs and the large size of the shrubs. An experimental layout that contained even more sampling points and facilitated more efficient data collection would be an improvement. Also the sampling area should be larger than a total of 20 m^2 annually per site.

Dimension analysis provides a valuable estimate of standing biomass, however if a more accurate estimate is required to meet study objectives, destructive measurements must be taken to provide adequate calibration criteria to support the allometric equations presented in Rittenhouse and Sneva (1977).

Clipping is, and most likely will always be, time consuming, especially when done by species, however there is no substitute for accurate field-collected yield data. In this study, separating the new growth on each shrub took as much or more time than clipping the vegetation. This presented a challenge in timing the collection of vegetation so that all the new growth could be removed before the collected vegetation dried out too much and determining new growth using the principles detailed above was no longer possible. The representative weight unit method used in this study was effective at reducing time required, both in the field and in the lab and is a promising option for further use when collecting yield data. Another promising method that has been tested more extensively is the NRCS endorsed double-sampling method (Butler et al., 2003). The double-sampling method would improve efficiency in the field by reducing the need to clip all plots while also increasing the number of sampling points.

It should be noted that without a known population or entity it is not possible to determine the accuracy of collected data. For all data collected, except perhaps LAI and soil moisture, known entities are not known from which accuracy can be determined and the method objectively evaluated. Instead a focus should be placed on precision and the collection of high quality data in quantities large enough to provide highly precise measurements of key vegetation attributes.

CONCLUSION

A reliable, accurate vegetation production forecasting system could revolutionize land and livestock management. Private land owners whose livelihood depends on the yearly growth of range plants would be able to make more informed decisions as they strive to meet land management and financial objectives. The freedom of meeting or exceeding financial objectives as a result of an improved, better informed decision making process would provide land managers with the confidence to make objective decisions regarding the land and how to best achieve management objectives. A reliable, accurate vegetation production forecasting system would also aid restoration personnel by allowing the planning of restoration projects at a time when the projects are most likely to be successful. The improved ability to plan and adapt to the challenges restoration personnel face would provide the opportunity for more effective spending on restoration projects and reduced fiscal waste.

A reliable, accurate vegetation production forecasting system would give land management agency personnel, including the Bureau of Land Management (BLM) and the U.S. Forest Service (USFS), the ability to use scientifically defensible decision making criteria to determine stocking rates during drought. An accurate system that forecasts plant growth could be incorporated into environmental assessments, to provide flexible stocking rates that are defensible under the National Environmental Policy Act, but also take advantage of above average production years and protect the land during below average years. A highly defensible, scientifically based land management decision making system would provide the opportunity for stronger legal defenses against lawsuits brought against federal, state, and other land management agencies.

LITERATURE CITED

Baret, F., B. de Solan, R. Lopez-Lozano, K. Ma, and M. Weiss. 2010. GAI estimates of row crops from downward looking digital photos taken perpendicular to rows at 57.5^{o} zenith angle: Theoretical considerations based on 3D architecture models and application to wheat crops. *Agricultural and Forest Meteorology* (150:1393-1401)

Breda, N.J.J.2003. Ground-based *measurements* of leaf area index: a review of methods, instruments and current controversies. *Journal of Experimental Botany* 54:2403-2417

Butler, L.D., J.B. Cropper, R.H. Johnson, A.J. Norman, G.L. Peacock, P.L. Shaver, and K.E. Spaeth. 2003. National Range and Pasture Handbook. Fort Worth, TX, USA. NRCS Grazing Lands Technology Institute.

Clark, P.E. and M.S. Seyfried. 2001. Point sampling for leaf area index in sagebrush steppe communities. *Journal of Range Management* 54:589-594

Cleary, M.B., E. Pendall, and B.E. Ewers. 2008. Testing sagebrush allometric relationships across three fire chronosequences in Wyoming, USA. *Journal of Arid Environments* 72:285-301

Coulloudon, B., K. Eshelman, J. Gianola, N. Habich, L. Hughes, C. Johnson, M. Pellant, P. Podborny, A. Rasmussen, B. Robles, P. Shaver, J. Spehar, and J. Willoughby. 1996. Sampling Vegetation Attributes: Bureau of Land Management TR 1734-4 172p.

Elzinga, C.L., D.W. Salzer, J.W. Willoughby, and J.P. gibbs, 2001 Monitoring plant and animal populations. Blackwell Science, Inc. Malden, MA. 492p.

Fernandez, R.J., O.E. Sala, and R.A. Golluscio. 1991. Woody and herbaceous aboveground production of a Patagonian steppe. *Journal of Range Management* 44:434-437

Hanson, C.L. 2001. Long-term precipitation database, Reynolds Creek Experimental Watershed, Idaho, United States. *Water Resources Research* 37:2831-2834

Hanson, C.L., D. Marks, and SS. Van Vactor. 2001. Long-term climate database, Reynolds Creek Experimental Watershed, Idaho, United States.

Herrick, J.E., J.W. VanZee, K.M. Havstad, L.M. Burkett, and W.G. Whitford. 2005. Monitoring Manual for Grassland, Shrubland, and Savanna Ecosystems, Volume II. Las Cruces, NM, USA: USDA-ARS Jornada Experimental Range. 200 p.

Hillel, D. 1998. Environmental soil physics. San Diego, CA, USA: Elsevier 771p.

Holecheck, J.L., R.D. Pieper, and C.H. Herbel. 2001. Range management: principles and practices. Upper Saddle River, NJ, USA: Prentice Hall 587p.

Kirkham, M.B. 2005. Principles of soil and plant water relations. Burlington, MA, USA: Elsevier, Inc. 500 p.

Larcher, W. 2003. Physiological Plant Ecology. Berlin, Germany: Springer-Verlag 531 p.

Rittenhouse, L.R. and F.A. Sneva. 1977. A technique for estimating big sagebrush production. *Journal of Range Management* 30:68-70

Seefeldt, S.S. and D.T. Booth. 2006. Measuring plant cover in sagebrush steppe rangelands: a comparison of methods. *Environmental Management* 37:703-711

Seyfried, M. S., M. D. Murdock, C. L. Hanson, G. N. Flerchinger, and S. Van Vactor. 2001. Long-term soil water content database, Reynolds Creek Experimental Watershed, Idaho, United States. *Water Resources Research* 37: 2847-51.

Slaughter, C.W., D. Marks, G.N. Flerchinger, S.S. VanVactor, and M. Burgess. 2001. Thirty-five years of research data collection at the Reynolds Creek Experimental Watershed, Idaho, United States. *Water Resources Research* 37:2819-2823

University of Nebraska, Lincoln. 2006. Available at: http://www.drought.unl.edu/whatis/predict.htm. Accessed 24 November 2010.

USDA, NRCS. 2010. The PLANTS database. Available at: http://plants.usda.gov. Accessed 22 November 2010.

VanAmburg, L.K., D.T. Booth, M.A. Weltz, and M.J. Trlica. 2005. A laser point frame to measure cover. *Rangeland Ecology and Management* 58:557-560

Wilson, J.W. 1959. Analysis of the spatial distribution of foliage by two-dimensional point quadrats. *New Phytologist* 58:92-99

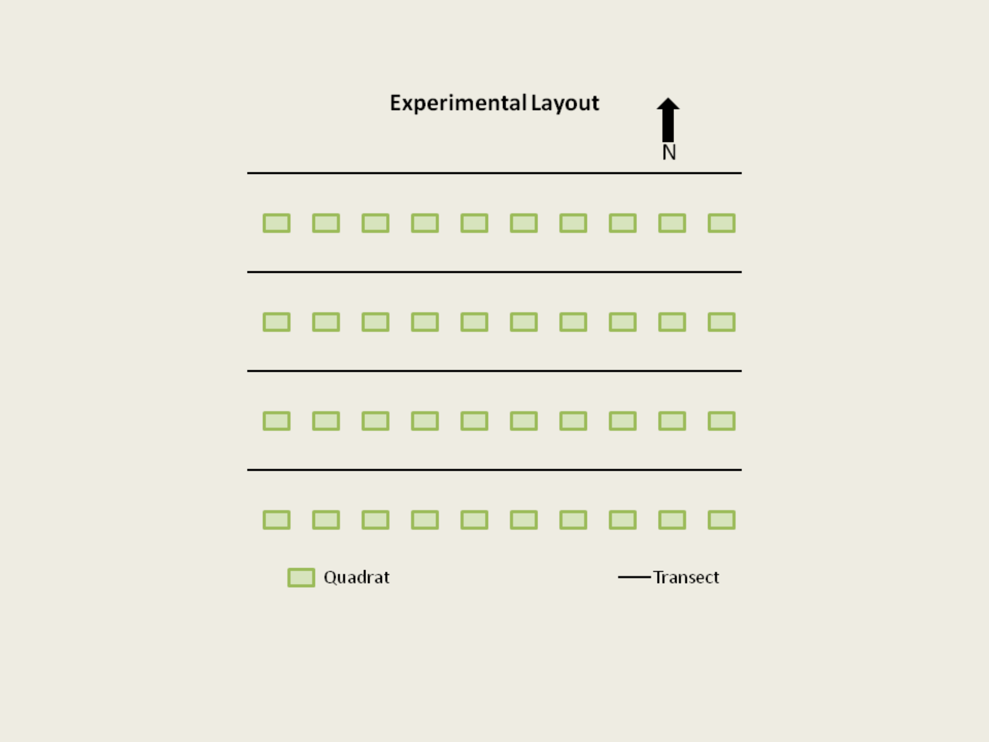

Figure 13: The experimental layout used in this study consisted of four 50 m transects 10 to 25 m apart with 10 quadrats per transect. Quadrats were spaced 5 m apart, offset from the transect 5 m and started at the 3 m measurement. In 2009, quadrats were placed on the south side of the transects and in 2010, quadrats were placed on the north side of the transects.

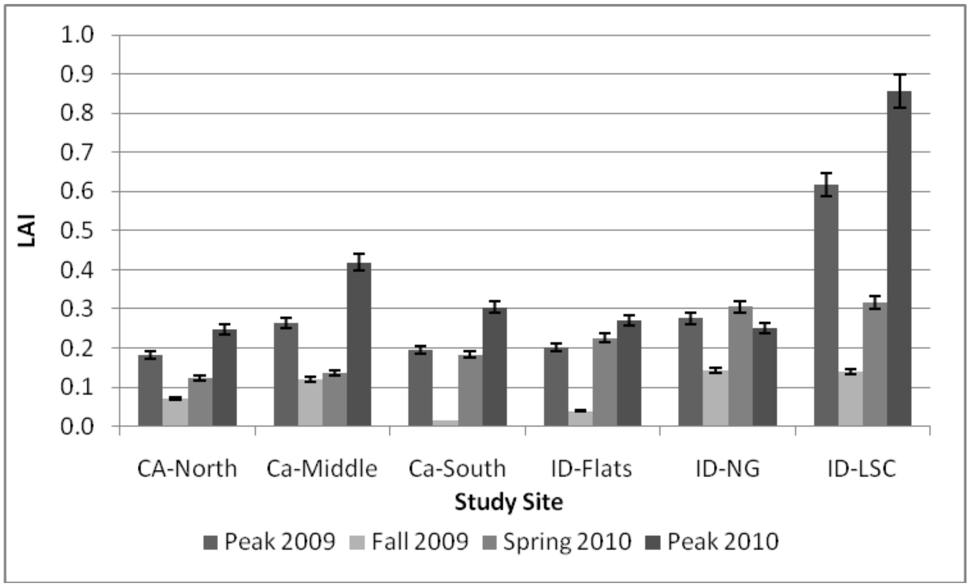

Figure 14: Leaf area index (LAI) values for study sites at peak standing crop in 2009, in fall 2009, spring 2010 and at peak standing crop in 2010. Error bars represent a 5% confidence interval.

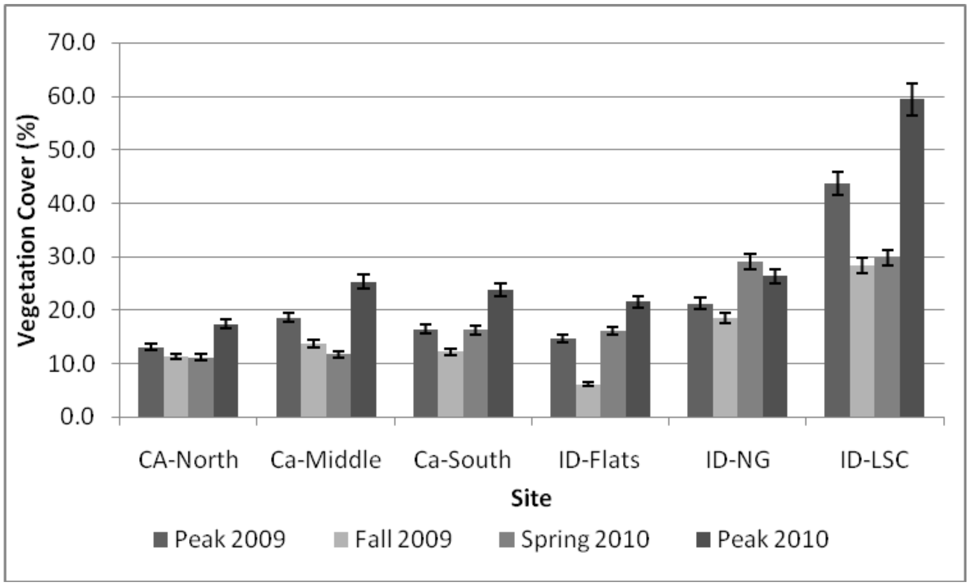

Figure 15: Percent vegetation cover at study sites for all sampling periods: peak standing crop 2009, fall 2009, spring 2010, and peak standing crop 2010. Error bars represent a 5% confidence interval.

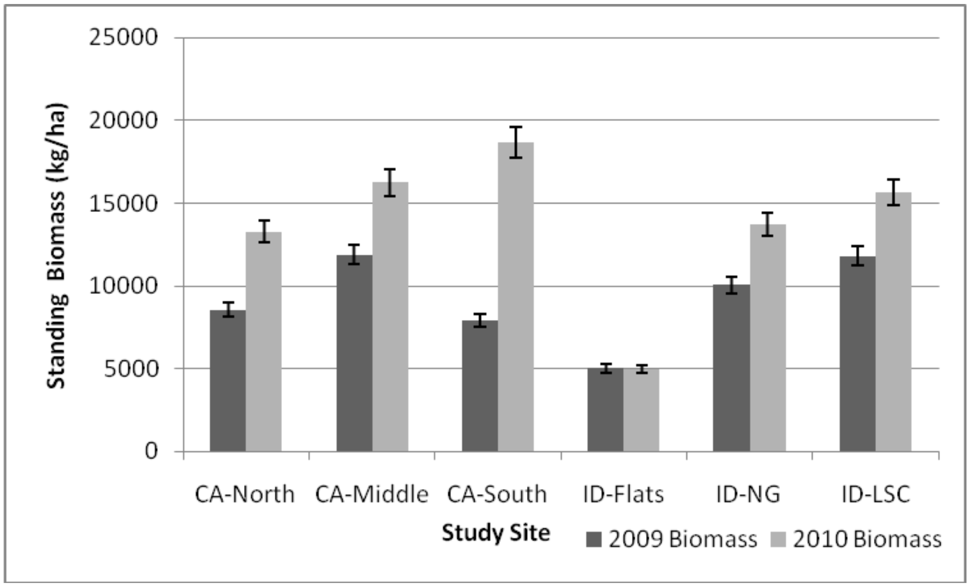

Figure 16: Estimated standing biomass at study sites in 2009 and 2010. Error bars represent a 5% confidence interval.

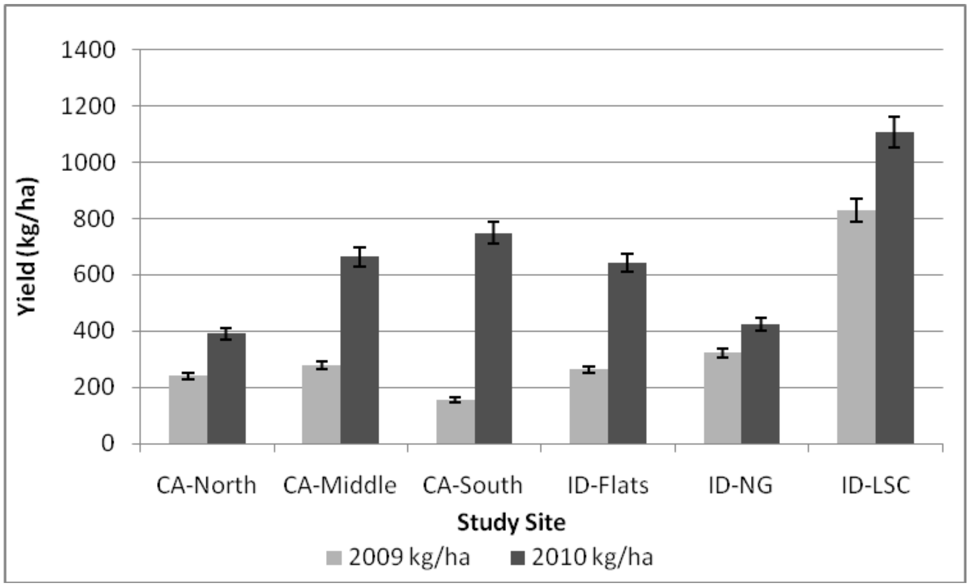

Figure 17: Vegetation yield at study sites in California and Idaho at peak standing crop in 2009 and 2010. Error bars represent a 5% confidence interval.

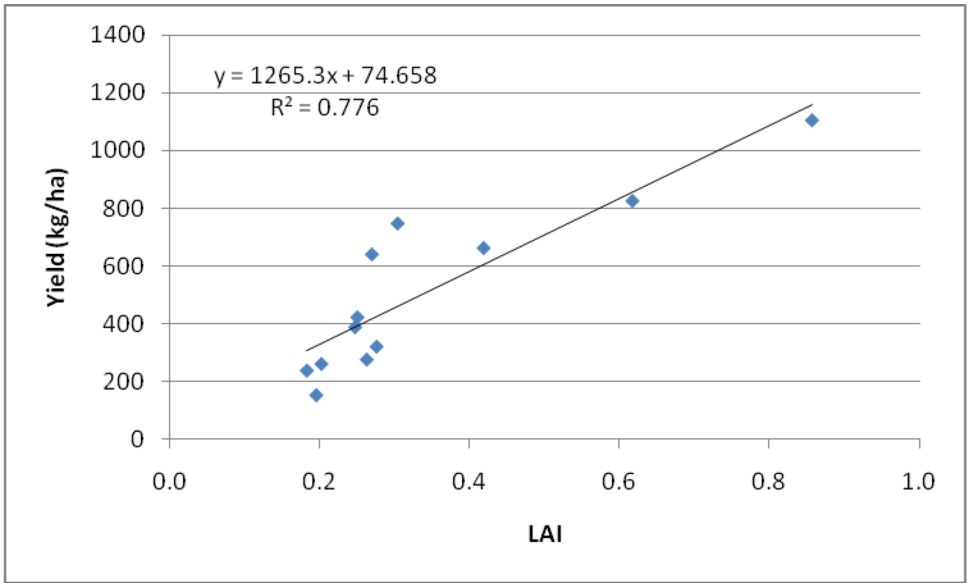

Figure 18: Leaf area index (LAI) plotted against Yield (kg/ha) to define the relationship between the two datasets. Data points represent peak standing crop measurements in 2009 and 2010.

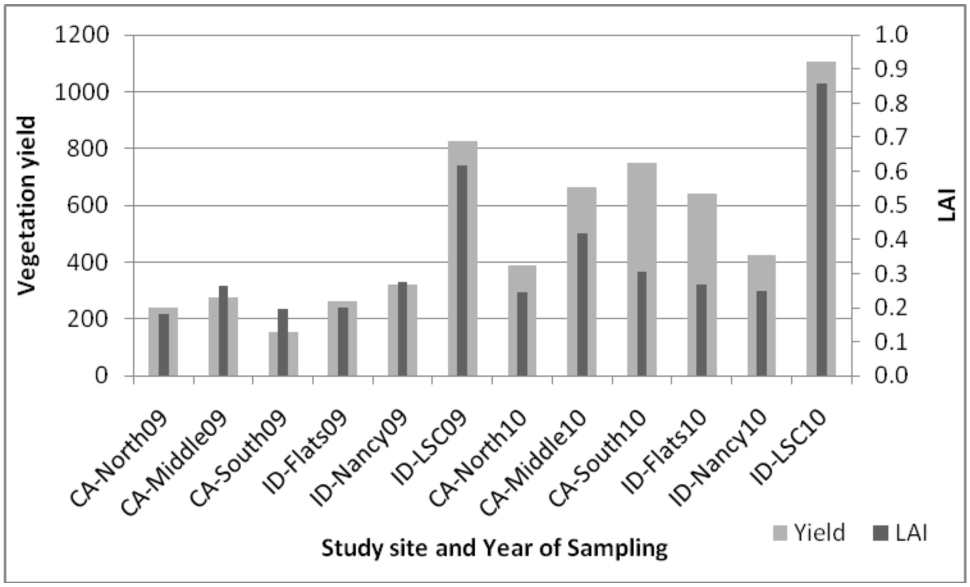

Figure 19: Leaf area index (LAI) and vegetation yield at study sites from samplings at peak standing crop in 2009 and 2010, plotted against each other for comparison.

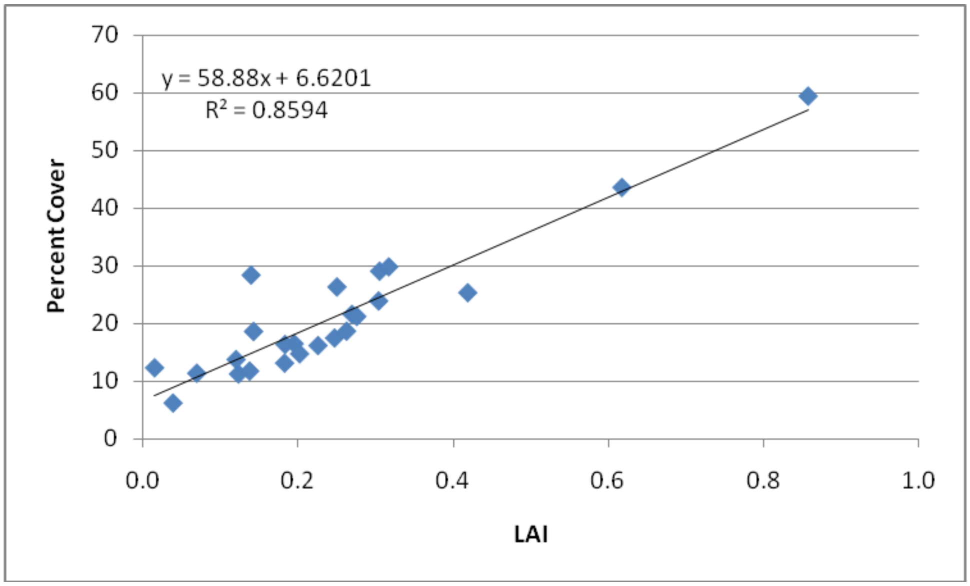

Figure 20: Leaf area index (LAI) plotted against percent cover to define the relationship between the two datasets. Data points represent measurements taken at all sampling periods in 2009 and 2010 at the six study sites, three in Idaho and three in California.

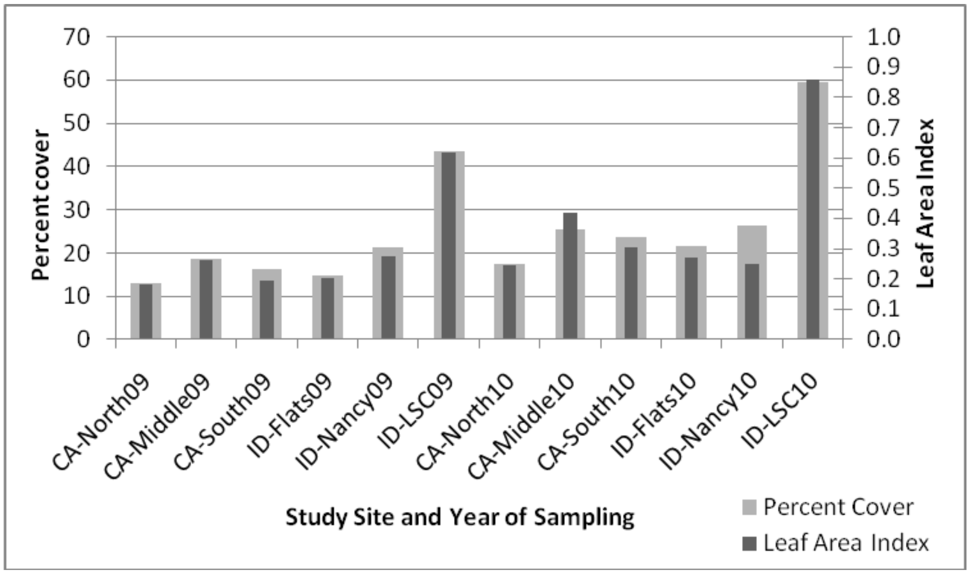

Figure 21: Leaf area index (LAI) and percent cover at peak standing crop in 2009 and 2010.

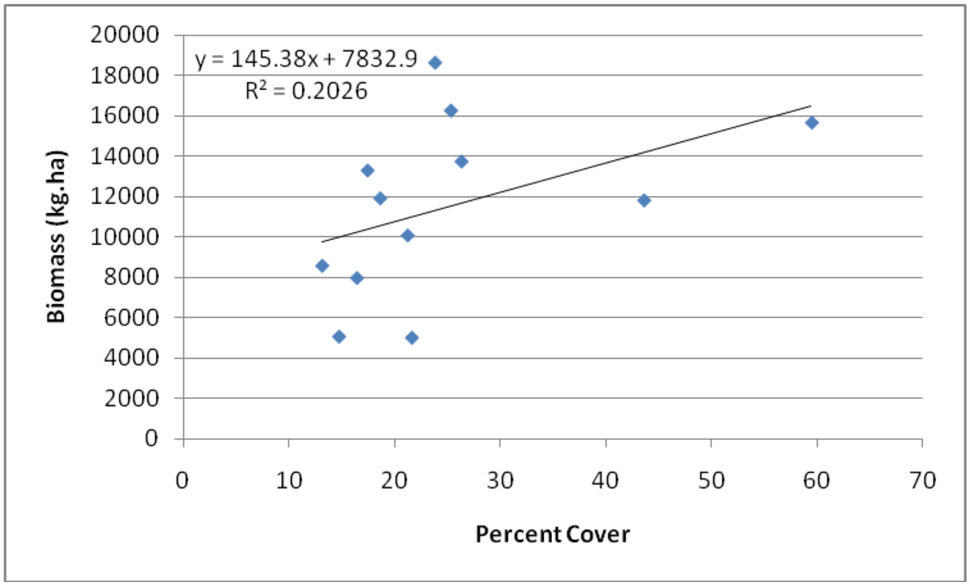

Figure 22: Percent vegetation cover plotted against estimated standing biomass to quantify the relationship. Data points represent peak standing crop in 2009 and 2010 at all study sites.

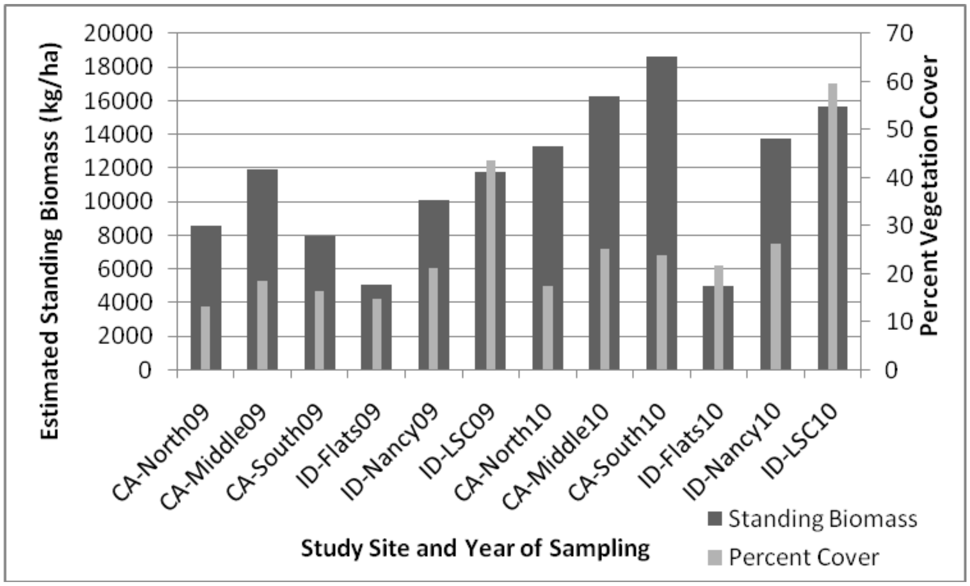

Figure 23: Percent vegetation cover and estimated standing biomass at peak standing crop in 2009 and 2010 plotted together for comparison.

Conclusion

The successful Soil Ecohydrology Model (SEM) simulations of soil moisture indicate that SEM could be just as successful forecasting yield. The methods reviewed for measuring vegetation attributes could provide the calibration and validation data needed for site-specific model input criteria and for testing model yield forecasts. A number of methods of measuring leaf area index (LAI) were reviewed and two were tested. Given the information provided researchers can decide to continue using the methods tested or utilize a different method. The comparisons made between LAI and percent cover, and LAI and yield could be very useful for the development of methods that are more easily applied.

The overall objective of this project was to begin the process of developing a vegetation forecasting system that was accessible to the end-user, hands-on land managers. Hands-on land managers, like ranchers, face temporal and financial constraints that a successful vegetation forecasting system must fit within if it is to be used. This study focused on laying the scientific groundwork for the development of a vegetation forecasting system that would fit the temporal and financial constraints hands-on land managers face.

To access the data collected during this project please contact the USDA, Agricultural Research Service at the Northwest Watershed Research Center, by writing to:

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