1-1-2008

Predicting evapotranspiration from sparse and dense vegetation communities in a semiarid environment using Ndvi from satellite and ground measurements

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PREDICTING EVAPOTRANSPIRATION FROM SPARSE AND DENSE VEGETATION COMMUNITIES IN A SEMIARID ENVIRONMENT USING NDVI FROM SATELLITE AND GROUND MEASUREMENTS

by

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A dissertation submitted in partial fulfillment
of the requirements for the

Doctor of Philosophy Degree in Biological Sciences
School of Life Sciences
College of Sciences

Graduate College
University of Nevada, Las Vegas
December 2008

UNLV
UNIVERSITY OF NEVADA LAS VEGAS

Dissertation Approval
The Graduate College
University of Nevada, Las Vegas

October 17, 2008

The Dissertation prepared by

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Entitled

Predicting Evapotranspiration from Sparse and Dense Vegetation Communities in a Semiarid Environment using NDVI from Satellite and Ground Measurements

is approved in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Biological Sciences

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1017-52

ABSTRACT

Predicting Evapotranspiration from Sparse and Dense Vegetation Communities in a Semiarid Environment using NDVI from Satellite and Ground Measurements

by

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One of the most critical issues associated with using satellite data-based products to study and estimate surface energy fluxes and other ecosystem processes, has been the lack of frequent acquisition at a spatial scale equivalent to or finer than the footprint of field measurements. In this study, we incorporated continuous field measurements based on using Normalized difference vegetation index (NDVI) time series analysis of individual shrub species and transect measurements within 625 m^2 size plots equivalent to the Landsat-5 Thematic Mapper spatial resolution. The NDVI system was a dual channel SKR-1800 radiometer that simultaneously measured incident solar radiation and upward reflectance in two broadband red and near-infrared channels comparable to Landsat-5 TM band 3 and band 4, respectively. The two study sites identified as Spring Valley 1 site (SV1) and Snake Valley 1 site (SNK1) were chosen for having different species composition, soil texture and percent canopy cover.

NDVI time-series of greasewood (*Sarcobatus vermiculatus*) from the SV1 site allowed for clear distinction between the main phenological stages of the entire growing season during the period from January to November, 2007. Comparison of greasewood NDVI values between the two sites revealed a significant temporal difference associated with early canopy development and early dry down of greasewood at the SNK1 site. NDVI time series values were also significantly different between sagebrush (*Artemisia tridentata*) and rabbitbrush (*Chrysothamnus viscidiflorus*) at SV1 as well as between the two bare soil types at the two sites, indicating the ability of the ground-based NDVI to distinguish between different plant species as well as between different desert soils based on their moisture level and color. The difference in phenological characteristics of greasewood between the two sites and between sagebrush, rabbitbrush and greasewood within the same site were not captured by the spatially integrated Landsat NDVI acquired during repeated overpasses. Greasewood NDVI from the SNK1 site produced significant correlations with many of the measured plant parameters, most closely with chlorophyll index ($r = 0.97$), leaf area index ($r = 0.98$) and leaf xylem water potential ($r = 0.93$). Whereas greasewood NDVI from the SV1 site produced lower correlations ($r = 0.89$, $r = 0.73$), or non significant correlations ($r = 0.32$) with the same parameters, respectively. Total percent cover was estimated at 17.5% for SV1 and at 63% for SNK1.

Transect measurements provided detailed information with regard to the spectral properties of shrub species and soil types, differentiating the two sites, which was not possible to discern with the spatial resolution of Landsat. Correlation between transect NDVI data and Landsat NDVI produced an r of 0.79. While correlation between transect NDVI data and ground-based NDVI sensors produced an r of 0.73. The linear regression equation between daily ET measured by the eddy covariance method and Landsat NDVI yielded a strong relationship ($r = 0.88$) for data combined across the experimental period (May to September) and across the two sites. The ET prediction equation was improved ($r^2 = 0.86$) by introducing net solar radiation (R_n) which was the meteorological variable that had the highest prediction of ET ($r^2 = 0.82$). A high correlation was found between weighted ground-based sensor NDVI estimates and Landsat derived NDVI at the pixel scale ($r = 0.97$) for the two study sites combined over time. While results from this study in scaling ground-based NDVI measurements and estimating ET were very promising, further verification and improvement is needed to determine the performance level of this approach over larger heterogeneous areas and over extended time periods.

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ACKNOWLEDGEMENTS

I would like to thank my dissertation advisor Dr. Dale Devitt for his proof reading of the manuscript, for his guidance and advice throughout the course of the PhD program. Without his indispensable advice and incredible patience and wisdom, I would never have been able to finish this arduous task or navigate through the turbulent days and the blinding moments of the PhD program. I take this opportunity to express my most profound gratitude and appreciation to Dr. Dale Devitt, because of his tireless efforts towards getting me to graduate, this great childhood dream of mine, is finally tuning into reality. My personal thanks to the committee members: Dr. Stanley Smith, Dr. David Kreamer, Dr. Paul Schulte and Dr. Lynn Fenstermaker for taking the time to evaluate this work.

I would like to acknowledge all the student workers and technicians in Dr. Devitt lab for their tremendous help with lab and field work. I would like to thank Southern Nevada Water Authority (SNWA) for funding this project. I would also like to thank the academic and professional staff of the School of Life Sciences, the UNLV Graduate College and the Office of International Students and Scholars.

CHAPTER 1

GENERAL INTRODUCTION

The research undertaken in this study was part of a long term study in the Great Basin (East-central Nevada) initiated in 2005, where normalized difference vegetation index (NDVI) derived from Landsat-5 TM imagery was used to estimate basin wide Evapotranspiration (ET). Utilization of remote sensing technology to estimate or scale long term environmental processes such as ET should be associated with different spatial, temporal and spectral resolution. Repeatable and continuous ground measurements are needed in order to gain further insight into the biophysical processes driving the NDVI signature.

The research approach implemented in this study was based on the integration of various remote sensing sensors with different spectral resolution to generate and compare NDVI values from sparse and dense vegetation settings and develop ET estimation models from spectral measurements acquired within the footprint of the eddy flux towers. The study was conducted in two different basins. One site in each basin was chosen based on having contrasting vegetation cover (sparse vs. dense, Figure 1). The sparse vegetation cover site consisted of a combination of greasewood (*Sarcobatus vermiculatus*), rabbitbrush (*Chrysothamnus viscidiflorus*), sagebrush (*Artemisia tridentata*) and shadscale (*Atriplex confertifolia*). While in the dense cover site, greasewood represented the dominant species.

Various plant, soil and meteorological measurements were taken every two weeks to estimate a number of physiological and environmental parameters. Remote sensing measurements obtained from various resolution sensors were analyzed and investigated at different temporal and spatial scales. The aim of this study was to provide a validation of Landsat derived NDVI and to understand the biophysical processes driving the NDVI signature during the growing season based on continuous and repeatable ground measurements.

The following are the tested hypotheses:

1. NDVI values will be higher at the SNK1 site and lower at the SV1 site. These differences will be consistent with total percent vegetation cover and ET values.

2. NDVI values obtained from ground-based sensors will show no significant difference between Greasewood from both sites. However the satellite data will show significant differences based on the difference in species composition between the two sites.

3. NDVI will also show an increasing pattern during the active growing period (May to June) and a decreasing pattern at the end of the summer (July to September) providing information about the growing period of each species and information about water stress on all monitored species at the end of the growing season.

4. NDVI values derived from ground-based sensors will be strongly correlated with plant measurements associated with green canopy cover and water content.

5. Linking detailed ground measurements to the NDVI-ET relationship integrated over the entire growing period will show that NDVI alone is not enough to accurately estimate ET. A quantitative relationship that includes ground biophysical and/or meteorological parameters and NDVI will enhance ET prediction.

6. NDVI values obtained from ground-based sensors can be scaled from single canopies and bare soil surfaces to an integrated satellite pixel NDVI basis within the footprint of the eddy flux towers using ground measurements as weighting factors.

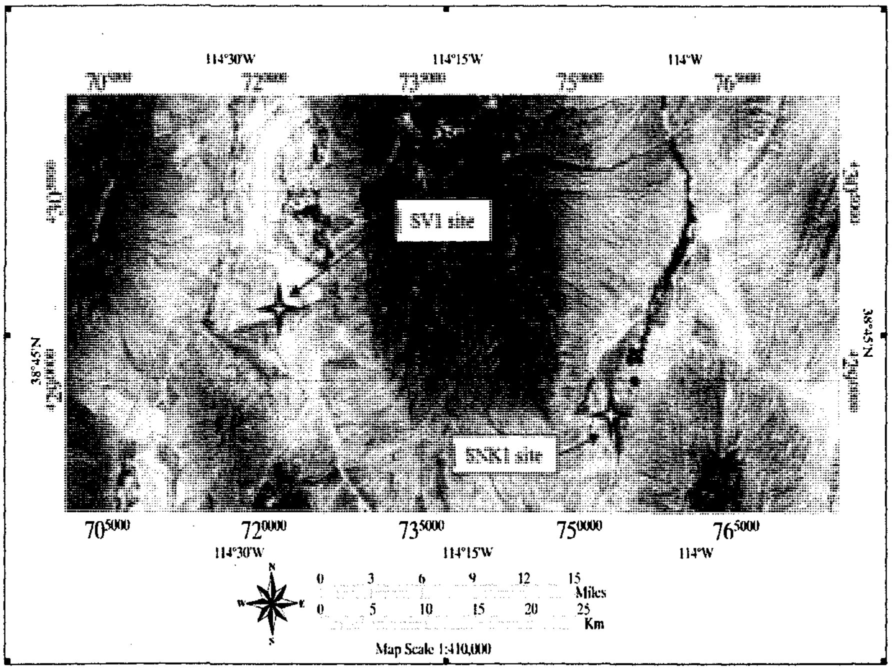

Figure 1. False color Landsat-5 TM image (2007) showing the location of the two study sites in the Great Basin.
The symbol indicates the approximate location of the study site center plots (25 m × 25 m) where the Eddy covariance tower was installed at the Spring Valley 1 site (SV1) and at the Snake Valley 1 site (SNK1).

CHAPTER 2

MONITORING VEGETATION PHENOLOGICAL CYCLES IN TWO DIFFERENT SEMI-ARID ENVIRONMENTAL SETTINGS USING A GROUND-BASED NDVI SYSTEM

Introduction

An extended hydrologic drought in the Colorado River has forced many communities in this region to seek additional water resources at greater distances. In the case of Southern Nevada, water rights applications have been filed for ground water in basins located in East-central Nevada; as such, more accurate water balances at the basin level are needed to make wise management decisions. In 2005 a long term study was initiated in the Great Basin of East-central Nevada (Spring Valley, White River Valley, and Snake Valley) to estimate basin-wide evapotranspiration (ET). Total ET during the growing season (May to September) was measured using Eddy covariance method and correlated with remotely sensed Landsat-5 Thematic Mapper data. A number of locations on the valley floors (within basins) were selected as experimental sites based on gradients in plant composition, percent cover, soil type and ground water depth. Highly significant linear relationships were found between the Normalized difference vegetation index (NDVI) and ET when data were combined across years (2005-2007) and across valleys (Devitt, unpublished data).

Current information shows that satellite-based remote sensing data has provided the ability to estimate and study ecosystem processes and surface energy fluxes such as ET over regional and global scales (Moran *et al.*, 1989; Nagler *et al.*, 2005b; McCabe & Wood, 2006). However, the limited temporal resolution of most satellite-based remote sensing platforms (data are acquired at a single point in time) and the relative coarse spatial resolution pose a potential problem in the reliability of such systems to provide continuous and accurate estimation of spatially distributed surface fluxes, especially in semi-arid regions characterized by land surface heterogeneity and incomplete vegetation cover. As part of our interest in interpreting the biophysical processes driving the spatial variation in ET-NDVI relationships, a field-based approach that allows for repeatable and continuous NDVI measurements at a much finer spatial and temporal scale than Landsat is needed.

In a semi-arid environment, although vegetation plays a critical role in the energy exchange between the land surface and the atmosphere via the transpiration process, it is accompanied by a significant amount of water loss via soil evaporation. In these regions, growing conditions can vary significantly based on the spatial variation in climate, water availability, vegetation composition and soil type. Plants are also highly responsive to short term and long term environmental factors and perturbations leading to temporal fluctuations in vegetation cover and density. Consequently, these inherent changes in vegetation characteristics affect the overall water balance and the spatial variation in ET-NDVI relationships.

Based on traditional remote sensing routines, visible and near-infrared (NIR) based vegetation indices (VIs) have been widely and successfully used in various ET estimation models (Seevers & Ottmann, 1994; Szilagyi, 2002; Loukas *et al.*, 2005; Nagler *et al.*, 2005a). The basis of using VIs to estimate a wide range of ecosystem processes is the underlying assumption shared by most of the remote sensing community, that the optical properties of terrestrial vegetation in the visible and NIR regions of the electromagnetic spectrum are key indicators of many physiological and biophysical processes. For instance, NDVI which is the normalized ratio of red and NIR spectral reflectance (NDVI = (NIR − RED) / (NIR + RED)), is one of the most widely and frequently used VIs in remote sensing research. As such, the existing global NDVI data derived from the NOAA`s Advanced Very High Resolution Radiometer (AVHRR) and the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite systems provide routine monitoring of terrestrial ecosystems and vegetation changes (Cihlar *et al.*, 1996; Justice *et al.*, 1998). NDVI has also been shown to be related to a number of plant physiological and biophysical parameters such as leaf area index (LAI), green vegetation density, biomass, chlorophyll content and photosynthetic activity as well as water content and overall vegetation health (Sellers *et al.*, 1992; Chuvieco *et al.*, 2004; Nagler *et al.*, 2004).

On the other hand, it is well known that NDVI has limitations when used to estimate canopy structural variations and architecture because it is potentially affected by soil background and it saturates at high biomass (Huete *et al.*, 2002; Jackson *et al.*, 2004) and at intermediate leaf area index values (Carlson & Ripley, 1997). Thus, the association of NDVI to greenness and chlorophyll content of the canopy, rather than to simple variations in LAI or percent canopy cover, has been well documented (Goward *et al.*, 1994; Glenn *et al.*, 2007). Uncertainties in interpreting NDVI data also occur in sparsely vegetated areas like semi-arid environments. These areas are characterized by open canopies with significant canopy background (leaf litter, dead branches, shadows and soil), making it difficult to isolate the green vegetation reflectance signal from the canopy background signal. Under such conditions, it becomes even more problematic when trying to interpret spatial and temporal differences over a diverse range of vegetation (Huete *et al.*, 2002). However, satellite NDVI was found to be reliable in monitoring and detecting seasonal variations in land cover (Ferreira & Huete, 2004; Telesca & Lasaponara, 2006). Additionally, Weiss *et al* (2004) and Hermance *et al* (2007) demonstrated the usefulness of NDVI time series to extract and track seasonal and inter-annual phenological behavior and changes of semi-arid vegetation.

The difficulties encountered in using large and infrequent synoptic remote sensing coverage to estimate and scale surface water and energy fluxes has led to the emerging realization in the last few years for the need of more reliable ground truthing techniques to provide a validation for satellite based data (Cheng *et al.*, 2006; Claudio *et al.*, 2006). An improved knowledge of the factors controlling the spatial and temporal changes in plant and soil reflectance properties often requires intensive and continuous field measurements at the canopy scale, which involves using high spectral resolution sensors. Typically, the use of conventional ground-based sensors such as portable spectroradiometers is often considered impractical for field studies associated with long-term flux measurements, mainly because they cannot continuously be applied at the same time across large spatial scales relevant to the corresponding satellite pixel or to the flux tower footprint without being engineered to operate automatically under various climatic and sky conditions.

The possibility of validating satellite data and linking them to flux tower point measurements was explored by Gamon *et al* (2006b), who lead the creation of the SpecNet (Spectral Network) initiative, an international network of automated optical field sampling systems aimed to link gas fluxes and other key ecosystem processes to optical remote sensing at a comparable scale at which eddy flux towers operate. As part of the SpecNet group, Hilker *et al* (2007) developed a fully automated tower-based spectral data collection system designed to measure year round spectral canopy reflectance at a high temporal frequency in a near 360° observation area around an eddy flux tower. This system was established 10 m above a forest canopy to provide a real time estimation of changes in plant pigment concentration. Gamon *et al* (2006a) developed an innovative approach by using an automated mobile field tram system to provide transect sampling for whole canopies and stands at a spatial and temporal scale comparable to the flux tower footprint.

In this study, continuous and repeatable ground-based measurements of soil and vegetation NDVI were taken across two contrasting sites in the Great Basin characterized by having a dense and a sparse vegetation cover. This setting provided as an ideal way to continuously monitor and compare NDVI changes between two sites where vegetation growth characteristics were highly affected by soil conditions (soil texture and moisture) and fluctuations in meteorological parameters and species composition. The approach engaged herein focuses on understanding the biophysical and spectral properties of the main constituents of each site (bare soil and vegetation). The main objectives were to address a number of questions such as: how do continuous and repeatable NDVI measurements of bare soil and key plant species, obtained at a much finer spatial and temporal scale than Landsat, vary between the two sites? What are the possible factors associated with the dynamics of plant growth stages that may influence the spatial variation in NDVI during the growing season between the two sites? To what extent does ground-based NDVI capture subtle key features and transitions in plant and soil biophysical properties during the growing season not captured by the coarse spatial resolution of Landsat data or information that is lost in the gap between satellite overpasses or not fully evaluated because of cloud cover?

Materials and methods

Description of study sites

The study was conducted at individual sites in two Great Basin valleys (East central Nevada) located 34 km apart and identified as Spring Valley 1 site (SV1) characterized by having a sparse vegetation cover (38° 46' 32.79" N 114 ° 28' 7.65" W, elevation: 1761.6 m) and Snake Valley 1 site (SNK1) characterized by having a dense vegetation cover (38° 41' 51.98" N 114 ° 5' 19.32" W, elevation: 1684.9 m), (Figure 1). The climate was typically semi-arid with cold winters and hot summers. The region receives the majority of its precipitation during winter months but also receives summer rainfall (between July and September) associated with the Southwest U.S. monsoon season. Selection of the two study sites was based on providing a contrast in species composition, percent canopy cover and density of greasewood (*Sarcobatus vermiculatus)* as well as differences in soil textural properties.

Detailed species composition identification and percent cover data were acquired at each site during the 2007 active growing season by manually identifying plant species and calculating the surface area of every individual plant within 25 m × 25 m plots corresponding to the Landsat-5 TM pixel size. At the SV1 site, the sparse vegetation cover consisted of a combination of greasewood (*Sarcobatus vermiculatus)*, rabbitbrush (*Chrysothamnus viscidiflorus*), sagebrush (*Artemisia tridentata*) and shadscale (*Atriplex confertifolia*), with sagebrush representing the dominant species. At the SNK1 site, with the exception of a few shrubs of shadscale, greasewood represented the dominant species.

<u>Micrometeorological measurements</u>

Fully equipped Eddy covariance micrometeorological towers (Campbell Scientific, Logan, UT, USA) were installed within the 25 m by 25 m center plot at each site. Water fluxes were measured using a 3D sonic anemometer (CSAT3, Campbell Scientific, Logan, UT, USA) along with an open path infrared gas analyzer (IRGA- Licor Biosciences, Lincoln, NE, USA) allowing for a surface energy balance approach to be used: $R_n = G + H + LE$

where, R_n, G, H and LE are the flux densities of net radiation (REBS net radiometer), soil heat storage (Hukseflux soil heat-flux plates), sensible heat (CSAT3, 3-D sonic anemometer) and latent heat, respectively (W m^{-2}). Post data processing of the 10 Hz data was accomplished using EdiRe (Clement & Moncreif, 1999). Standard corrections were made following the protocol outlined by AmeriFlux (Lee *et al.*, 2004). Hourly and daily averaged air temperature, wind speed, relative humidity, solar radiation and precipitation data were acquired from automated weather stations at both monitoring sites. Potential evapotranspiration (ET_o) was calculated using the Penman-Monteith equation (Monteith & Unsworth, 1990) to assess environmental evaporative demand.

Satellite data

Terrain corrected and georectified Landsat 5 TM images were purchased from the U.S. Geological Survey- Earth Resources Observation and Science (USGS-EROS) Data Center. Acquisition dates for the 2007 growing season were: April 13, April 29, May 15, May 31, June 16, July 2, July 18, Aug. 3, Aug. 19, Sep. 4 and Sep. 20. The image processing software: Environment for Visualizing Images (ENVI), (Research Systems, Inc., Boulder, CO, USA) was used for image processing including calibration and atmospheric correction. The selected atmospheric correction method was based on the empirical line method (ELM) where field spectra (light, dark and medium targets) acquired on a single date (June 20, 2007) were resampled and used to atmospherically correct and normalize Landsat band 3 and band 4 for all dates. The resulting reflectance data were then used to calculate NDVI. At each site and for every acquisition date, NDVI values were extracted from the pixel representing the plot where the ground-based NDVI sensors were located.

Ground-based NDVI system

Ground- based NDVI measurements were carried out using a dual channel SKR-1800 radiometer (Skye instruments LTD, Powys, UK) that simultaneously measures incident solar radiation (sensor 1) and upward reflectance (sensor 2), thus correcting for solar variations. The two sensors were fitted with a removable cosine-corrected diffuser which serves the purpose of measuring downwelling light in accordance with Lambert`s cosine law. Thus, when taking incident light measurements, the diffuser head is left in place. However, for the measurements of reflected light energy, the cosine diffuser head can be removed or kept in place depending on the size of the area to be viewed. For instance, when the diffuser cap is removed, the light acceptance of the sensor becomes narrow angle cone shaped with a defined 25° field of view (FOV) which is suitable for measuring reflectance properties of soil and vegetation surfaces. In both cases, the measured reflectance area can also be defined by adjusting sensor height above the viewed ground surface.

The SKR-1800 radiometer used in this study was customized by the manufacturer upon our request to acquire data in two broadband channels: channel 1(red): 630-690 nm and channel 2 (NIR): 760-900 nm, both comparable to Landsat- 5 TM band 3 (red) and band 4 (NIR) bandwidth, respectively. Sensor calibration was done by the National Physical Laboratory, UK in 2007 prior to use. All SKR-1800 sensors were installed within a 25 m by 25 m plot adjacent to the center plot within the footprint of the Eddy flux towers.

At the SV1 site, sensors (upwelling and downwelling) were mounted above the canopy of an individual greasewood plant with data collection beginning in January of 2007 prior to the start of field data collection in May, whereas, at the SNK1 site sensors were installed in the beginning of May. In all cases, sensors were mounted on horizontal beams attached to vertical stainless steel poles, with the downward looking sensor positioned above single greasewood, rabbitbrush, sagebrush canopies and a bare soil surface at the SV1 site and above a greasewood canopy and a bare soil surface at the SNK1 site, all representing satellite image pixel components at the larger scale. In this study, all cosine-corrected diffuser caps were removed from the sensors measuring reflected radiance. Consequently, for each plant canopy, the height of the downward looking sensor was adjusted based on the size of the monitored plant (Table 1). All horizontal beams with sensors were slightly oriented to the southwest to avoid shadow effects. Although the sensors were automated and required minimal attendance, periodic leveling checks, sensors adjustments and cleaning were made.

Table 1. NDVI sensor height and measured surface area of each ground surface.

Ground surface	Sensor height (cm)	Ground resolution (m^2)
Greasewood (*Sarcobatus vermiculatus*), (SV1)	1.71	0.43
Rabbit Brush (*Chrysothamnus viscidiflorus*), (SV1)	1.37	0.28
Sagebrush (*Artemisia tridentata*), (SV1)	0.98	0.14
Bare soil (SV1)	1.77	0.47
Greasewood (*Sarcobatus vermiculatus*), (SNK1)	1.48	0.33
Bare soil (SNK1)	0.75	0.09

All sensor serial cables were connected to a CR10X datalogger (Campbell Scientific, Logan, UT, USA) mounted on the weather station at each site. The datalogger stored the data on a removable SM4M storage module, allowing for quick and convenient retrieval of the data during routine field visits. For the purpose of data acquisition, we prepared a custom software program to automatically allow for real-time and continuous (24 hrs a day) collection of incident and reflected radiance at 1 min intervals. The output from each channel was in the form of current, proportional to the light falling on the sensor in $\mu mol\ s^{-1}m^{-2}$ (Skye instruments LTD, 2007). In order to make both channels equally sensitive for ratio measurements (Skye instruments LTD, 2007), the output from each channel and each individual sensor (with the diffuser head removed) was multiplied by a relative sensitivity factor (Z) provided in the manufacturer's calibration certificate.

In a final step, all the downloaded data was processed in the lab and NDVI was calculated as follows:

$$NDVI = \frac{(Z^* \, NIR_{R(nA)} * Y) - (Red_{R(nA)} * X)}{(Z^* \, NIR_{R(nA)} * Y) + (Red_{R(nA)} * X)}$$

where,

X: NIR_I incident reading (μmol $s^{-1}m^{-2}$)

Y: Red_I incident reading (μmol $s^{-1}m^{-2}$)

Z: Ratio sensitivity of reflected NIR: Red

$NIR_{R(nA)}$: Reflected reading in nanoamps

$Red_{R(nA)}$: Reflected reading in nanoamps

Soil and plant measurements

Plant biophysical and soil physical properties were acquired at both sites during midday hours every two weeks to coincide with Landsat overpasses. All measurements were taken within the 625 m^2 plot where the NDVI sensors were installed. For all plant measurements, three plants per species were monitored at each site. Plant canopy temperature (T_c) was measured using a hand-held 39800 infrared thermometer (Cole Parmer Instrument Company, Vernon Hills, IL, USA). Air temperature was measured at a 1m height near each monitored shrub and within canopy interspaces with an infrared thermometer (Cole Palmer Model 39800). Canopy-air temperature differentials ($T_c - T_a$) were then calculated to normalize the data against ambient conditions and assess plant water status. Canopy chlorophyll content was assessed using a portable CM 1000 chlorophyll index meter (Spectrum Technologies, Plainfield, IL, USA). Leaf xylem water potential (Ψ_ω) was measured with a 760 Model Pressure chamber (PMS instrument company, Albany, OR, USA). Leaf tissue samples were harvested from all species within the monitored plots and placed into pre-labeled and insulated plastic cups, sealed and transported to the lab where they were immediately weighed. Samples were then oven dried at 70 °C for 48 h to provide dry weight for tissue moisture estimation. Oven dried tissue samples were analyzed for total nitrogen concentration using the Total Kjeldahl Nitrogen (TKN) procedure outlined by Isaac & Johnson, 1976.

Leaf area index (LAI), an important biophysical variable of plant canopies is defined as the total one-sided area of leaf tissue per unit ground surface area (Watson, 1947). LAI was estimated using a Decagon AccuPAR-LP80 meter (Decagon Devices, Inc., Pullman, WA, USA). LAI values were generated by combining sensor measurements taken above and below the canopies. LAI in this study was monitored to assess the variations in canopy cover of each species at various phenological stages during the growing season to determine how these variations might influence NDVI measurements based on the intercepted light energy associated with leaf area.

Surface soil water content was estimated using an SM200 soil moisture sensor (Delta T-Devices, Cambridge, UK). Time domain reflectometry (TDR) probes (6050X1, Soil moisture equipment CORP., Goleta, CA, USA) were used to assess soil water content at depths of 15 cm, 45 cm, 75 cm and 105 cm (SV1 only).

All statistical analyses were based on descriptive statistics and on simple linear and multiple linear regression techniques using SigmaStat version 3.1 (SPSS Inc, Chicago, IL, USA). In this paper, all correlations were tested for significance at *P*-values ≤ 0.05. Backward stepwise regression analysis was also performed to determine which plant and/or soil parameters could account for the greatest amount of variation in measured NDVI values. In all cases, prediction equations were accepted only if the variance inflation factor (VIF) of individual predictors was <2 and the ∑VIFs for all predictors was <10.

Plant/soil parameters and ground-based NDVI data from the same dates of Landsat overpasses were detested for possible correlations using linear regressions. Results were considered to be statistically significant when the *P*-value ≤ 0.05. The observed difference in ground-based NDVI time series between the monitored plant species and the two soil data across the two sites were investigated using the t-test to determine whether the calculated means were statistically different.

In order to obtain the best prediction equation of ground-based NDVI between the two sites, all soil and plant variables were included in a set of multiple regression analyses. Backward regression analysis was performed to eliminate non-significant independent variables that did not correlate well with NDVI. Linear regression analysis was also conducted to determine which of the soil and/or plant parameters could account for the greatest amount of variation in NDVI. Results of each analysis were used to further check for autocorrelation and multicollinearity problems.

Coefficient of determinations (r^2) were used to explain the variability in a given parameter for all predictive regression equations. While correlation coefficients (r) were used to report the degree of correlation between two variables.

Results

Comparing vegetation NDVI trends between the two sites

To better understand the spatial and temporal patterns of phenological stages, average midday ground-based NDVI values (11:30 to 13:30 h) were calculated from daily data collected at two experimental sites during various monitoring periods in 2007 (Figure 2-1, 2-2 and 2-3). The temporal average midday pattern of NDVI for a single greasewood plant at the SV1 site was monitored for a 316 day period from January 19 to November 30, 2007 (Figure 2-1). This pattern reflected ongoing physiological and physical canopy changes, leading to five clear phases of growth. Phase (I) depicted a dormancy period prior to and after the active growth period associated with complete defoliation during the winter months. Phase (II) was associated with a rapid increase in NDVI values from 0.18 to 0.49 during the period from April 3 to June 6, indicating an active growth period facilitated by favorable growing conditions causing NDVI to reach peak values (0.48 to 0.50) towards the end of this phase. During phase (III), NDVI values remained quite stable, although they showed a slight decline towards the end of June and beginning of July depicting the first signs of the plant response to the summer dry period. However, a sharp increase in NDVI values occurred shortly thereafter, leading to a second prominent peak. This response occurred immediately after the first significant summer rainfall pulse on July 11 and continued throughout subsequent rain pulses on July 16, July 23, August 1 and August 2. In the remaining phases (IV and V), NDVI showed a gradual decline from 0.42 to 0.20. The trend in Phase (IV) was attributed to water stress response during the dry summer period associated with depletion of surface soil water and loss of canopy cover. Finally, phase (V) signified the end of the growing season associated with minimal physiological activity and leaf senescence with the exposure of background soil surface. The occasional "bumps" in NDVI values during these two final phases were associated with summer rainfall between August and September (Figure 2-1).

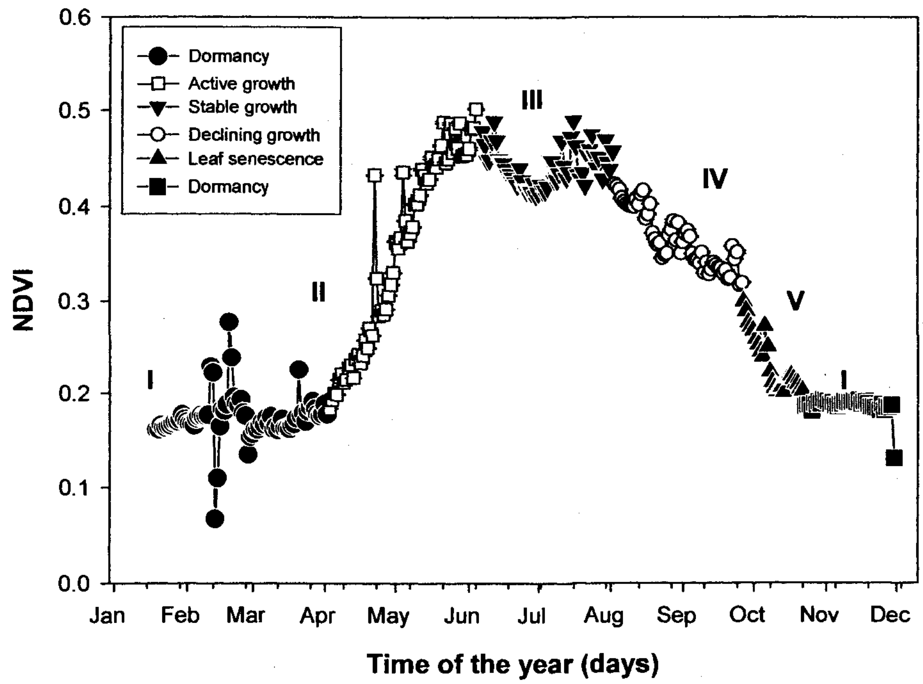

Figure 2-1. Time series of average midday (11:30-13:30h) NDVI values of a single greasewood plant at the Spring Valley 1 site.
Data were acquired for the period from January 19 to November 30, 2007.
I: dormancy phase (January 19-April 2); II: active growth and canopy development phase (April 3-June 6); III: full canopy development and stable physiological status phase (June 7-August 2); IV: water limitation and stress response phase (August 3-September 26); V: leaf senescence phase (September 27-October 22); I: dormancy phase (October 23-November 30).

A full NDVI time series response for the greasewood plant at the SNK1 site was not acquired, due to a delay in the sensor installation occurring in May 2007 and because of field problems encountered later in the season (October) associated with damage to serial cables by rabbits/rodents. Comparison of greasewood NDVI values at the SV1 site and the SNK1 site are shown in Figure 2-2 for the experimental period from May to September. In both cases, NDVI exhibited higher values during late spring and early summer (May to July) and lower values in mid-summer which continued to the end of September. The greasewood NDVI values from the SNK1 site were 1.3 to 1.8 fold higher than the greasewood NDVI values from the SV1 site during the period from May 5 to June 11. However, NDVI values were significantly higher (between 1.1 and 1.4 fold) at the SV1 site compared to the SNK1 site during the summer dry period between early August and late September. At the SNK1 site, NDVI values showed a very pronounced decline from maximum values of 0.60 and 0.68 during the month of May to 0.38 at the beginning of August to 0.14 by the end of September. During the exact same period, NDVI values measured at the SV1 site, showed little to no apparent decline from maximum values of 0.40 and 0.48 during the month of May to 0.42 at the beginning of August followed by a gradual decline reaching a minimum value of 0.27 by the end of September.

Based on field observations, the differences in NDVI values for the same species from the two different sites can be attributed in part to an early green up (phase II) of greasewood plants at the SNK1 site, followed by an earlier entry into the final stages of senescence. In general, the two NDVI curves (Figure 2-2) display similar shapes during the experimental period (May-September) with different daily NDVI values, reflecting site specific forces (soil moisture, nutrient availability, rainfall and environmental demand) controlling growth. However, calculating the area under the curve as an indication of an integrated total revealed that despite the decline in greasewood NDVI at SNK1 to lower values over the last two months of August and September, the earlier phase led to higher integrated totals (65.5 for SNK1 vs. 59.3 for SV1).

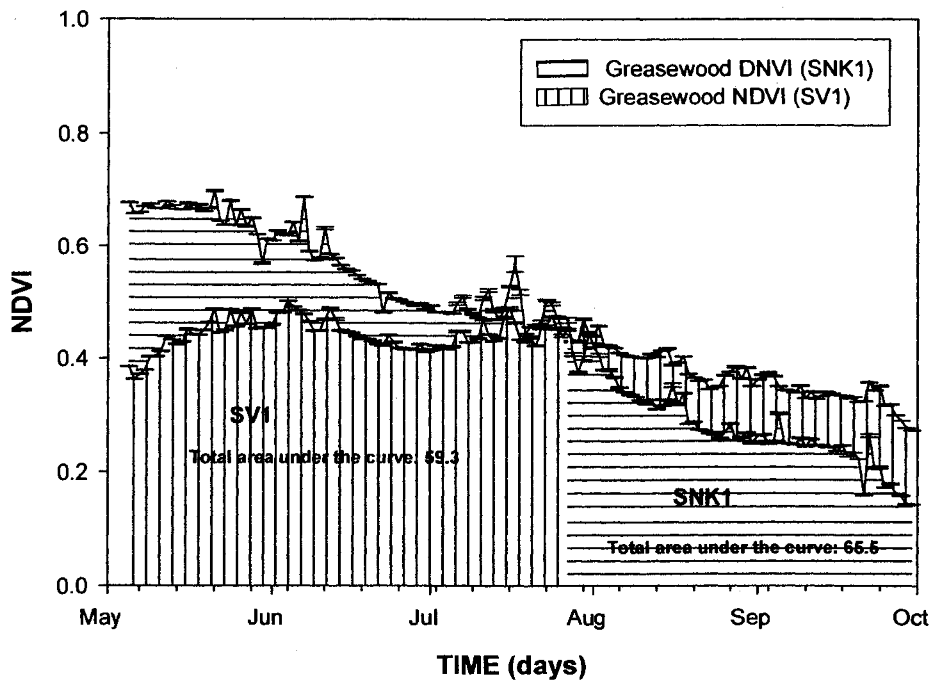

Figure 2-2. Time series of average midday (11:30-13:30h) NDVI values of a single greasewood plant at Spring Valley 1 site and at Snake Valley 1 site. Data were acquired during the experimental period from May 5 to September 30, 2007. The area under the curve represents an integrated greasewood growth total of 59.31 for the Spring Valley 1 site and 65.47 for the Snake Valley 1 site.

A comparison of NDVI between sagebrush and rabbitbrush for the period from May to November revealed four distinct phenological phases for sagebrush and five distinct phases for rabbitbrush (Figure 2-3). Sagebrush NDVI values were between 1.2 and 1.4 fold higher than rabbitbrush during the spring period (May to early-June) represented here as phase (I). During phase (II) sagebrush NDVI showed a gradual decline from 0.39 to 0.28 from June 5 to July 10 indicating a downward adjustment entering the summer period. In the case of rabbitbrush, phase (II) was relatively shorter than sagebrush (June 15 to July 2) but indicated the same type of downward adjustment prior to the peak summer period. During this shorter time period, rabbitbrush NDVI values declined from 0.36 to 0.27. Phase (III) was a period associated with relatively unchanging NDVI values for both sagebrush and rabbitbrush, ranging between 0.27 and 0.29 (July 3/11-October 10) except for the few peaks which occurred mainly in July following rainfall events. It is worth noting that rabbitbrush produced bright yellow flowers (from August through October) causing reflectance in the red regions of the electromagnetic spectrum to increase leading to lower NDVI values. However, in the remaining period (early-October and late-November) depicted as phase (IV), sagebrush which is an evergreen plant, revealed a very slow decline in NDVI values, maintaining significantly higher values (~0.24) during this early winter period. Whereas, in phase (IV), rabbitbrush NDVI continued to show a steady and clear decline to reach a value of 0.13 by mid November indicating a further downward adjustment as the plants entered early winter. Contrary to sagebrush, the NDVI time-series for rabbitbrush revealed one additional phenological stage (V) starting around mid-November. This stage had low and relatively unchanging NDVI values (~0.12) associated with the plants entering a period of full senescence (Figure 2-3).

The calculated area under the curve for sagebrush and rabbitbrush for the experimental period between May and September (same time period reported for greasewood) produced cumulative NDVI values of 44.8 and 41.0, respectively (data not shown) which were significantly lower than that reported for greasewood ($P<0.001$).

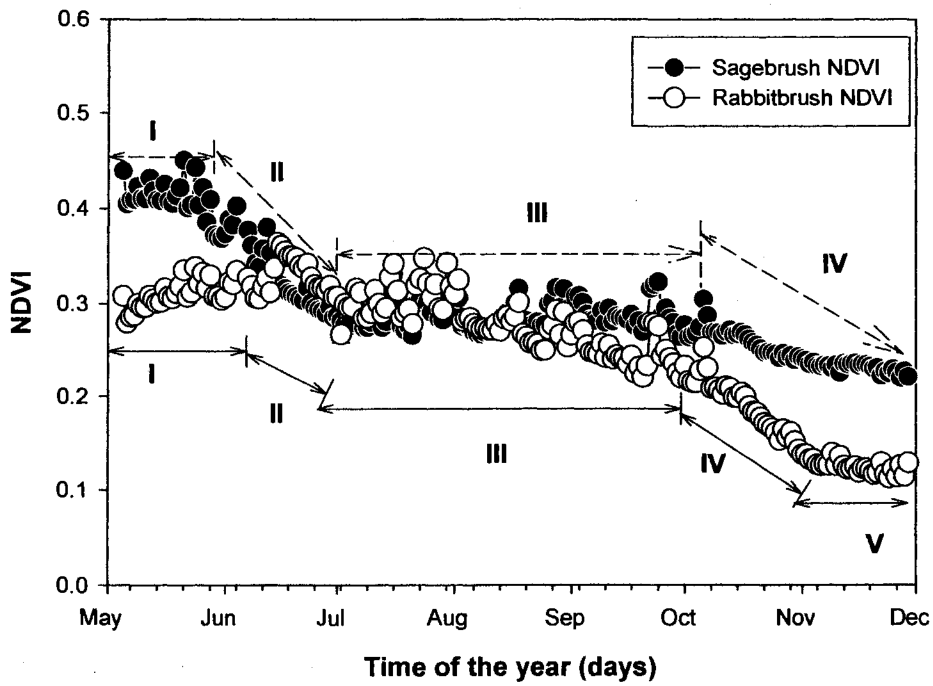

Figure 2-3. Time series of average midday (11:30-13:30h) NDVI values of a single sagebrush plant and a single rabbitbrush plant at Spring Valley 1 site.
Data were acquired from May 5 to November 30, 2007. I: active growth and canopy development (May 5-June 4 for sagebrush) and (May 5-June 14 for rabbitbrush); II: downward adjustment entering summer period (June 5-July 10 for sagebrush) and (June 15-July 2 for rabbitbrush); III: stable physiological status during summer period (July 11-October 7 for sagebrush) and (July 3-October 7 for rabbitbrush); IV: downward adjustment entering winter period (October 8-November 30 for sagebrush) and (October 8-November 4 for rabbitbrush); V: leaf senescence phase (November 5-November 30 for rabbitbrush).

Comparing soil NDVI trends between the two sites

Bare soil produced very low NDVI values ranging from less than 0.01 to 0.12 (Figure 2-4). There was a small but significant ($P<0.001$) difference in NDVI values between the two undisturbed soil surfaces observed for the entire experimental period. The NDVI soil values were significantly lower than those observed with the different plant species as previously described (Figure 2-1, 2-2 and 2-3). NDVI values were lower for the loamy sand soil (SV1 site) than for the loamy soil (SNK1 site) indicating that spectral reflectance properties of soils vary based on their surface characteristics such as texture (85.2% sand at SV1 vs. 42.6% sand at SNK1) and color (SV1 10YR 7/2 Light Grey, SNK1 10YR 6/3 Pale Brown). NDVI values showed some very pronounced peaks with different magnitudes throughout the experimental period associated with rainfall events, especially those that occurred on the same date at the two sites: June 5, July 11, 16 and 23; August 1, 2, 16, and 26 and on September 22 (Figure 2-4). Most of the NDVI peaks at the SV1 site were either smaller or less pronounced than those observed at the SNK1 site, except during the period of September 22, when higher rainfall amounts (24.89 mm day^{-1}) were recorded at the SV1 site. The soil NDVI peaks from the SNK1 site, usually lasted for a longer period of time following a rainfall event, while the NDVI peaks at the SV1 site typically disappeared after only a day or two. These differences in NDVI values were also due to the differences in spectral reflectance properties between dry and wet soils, with wet soils having lower visible and NIR reflectance than dry soils.

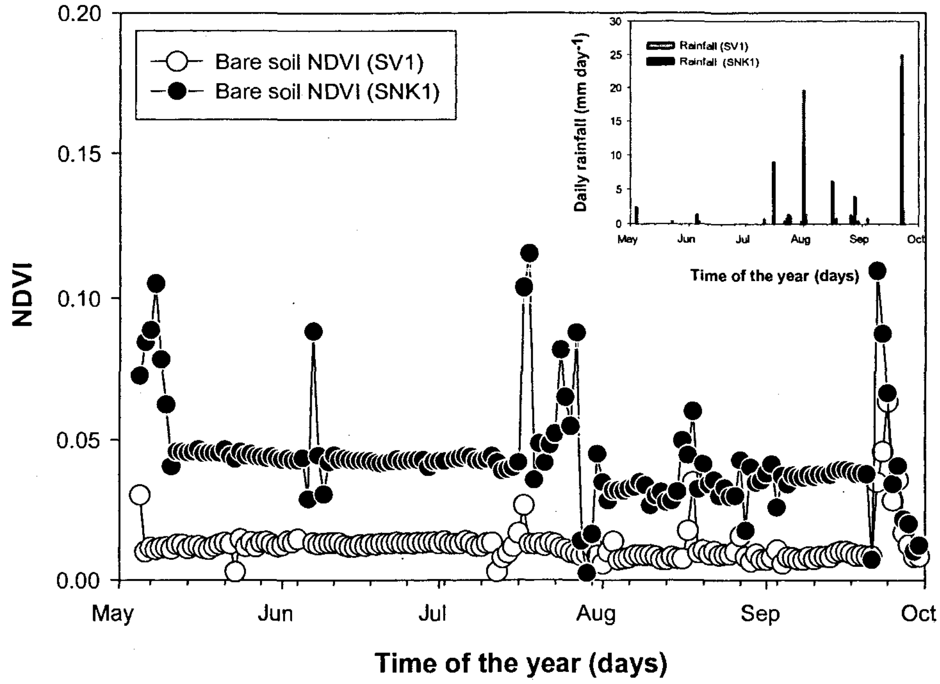

Figure 2-4. Time series of average midday (11:30-13:30h) NDVI values of a bare soil surface at Spring Valley 1 site and at Snake Valley 1 site.
Data were acquired during the experimental period from May 5 to September 30, 2007. Average daily rainfall data acquired from a weather station at the two sites are illustrated for the same experimental period.

Correlations between ground-based NDVI and soil-plant measurements

Possible linear and curvilinear relationships found between the ground-based calculated NDVI and the plant physiological and biophysical parameters measured during this study are illustrated in Figure 2-5. The correlations between greasewood NDVI at the SNK1 site with plant parameters were higher than those demonstrated for the SV1 site, except for tissue nitrogen concentration (TN). At the SNK1 site, greasewood NDVI showed a very strong correlation with the chlorophyll index ($r = 0.97$, $P < 0.001$),

(Figure 2-5A) and a significant relationship with TN ($r = 0.67$, $P < 0.001$), (Figure 2-5B). In both cases, the relationship was curvilinear suggesting that NDVI saturated (~ 0.67) at canopy chlorophyll index values higher than 178 and TN higher than 3 % (NDVI ~ 0.56). Greasewood NDVI from the SV1 site did not show the same saturation effect or the same curvilinear relationships, as greasewood canopies were not as green (field observations) at the SV1 site compared to the SNK1 site. Chlorophyll index highly correlated with NDVI (r: 0.89, $P < 0.001$) (Figure 2-5E) while TN showed a moderate correlation with the same variable (r: 0.69, $P < 0.001$), (Figure 2-5F) at the SV1 site.

A strong correlation existed between NDVI and leaf xylem water potential (Ψ_{ω}) at the SNK1 site ($r = 0.93$, $P < 0.001$) with NDVI values declining from 0.67 to 0.25 as Ψ_{ω} declined from -3 MPa to -4.9 MPa (Figure 2-5C). However, at the SV1 site, a very poor correlation was found between NDVI and Ψ_{ω} ($r = 0.32$) for greasewood (Figure 2-5G). When greasewood LAI was correlated with NDVI, the linear regression yielded an excellent correlation at the SNK1 site ($r = 0.98$, $P < 0.001$), (Figure 2-5D) but only a moderate correlation at the SV1 site ($r = 0.73$, $P < 0.001$), (Figure 2-5H). However, it should be noted that the LAI data set was small, representing only the later phases of growth (July-September).

When the relationships between plant parameters and NDVI were investigated for sagebrush and rabbitbrush at the SV1 site, sagebrush NDVI correlations were always higher than rabbitbrush (Figure 2-5) except for LAI (r of 0.96 for rabbitbrush and r: 0.77 for sagebrush; Figure 2-5H). However, estimating LAI was problematic in the case of rabbitbrush due to its canopy architecture characterized by erect, dense branching that made it difficult to obtain accurate leaf area index estimations.

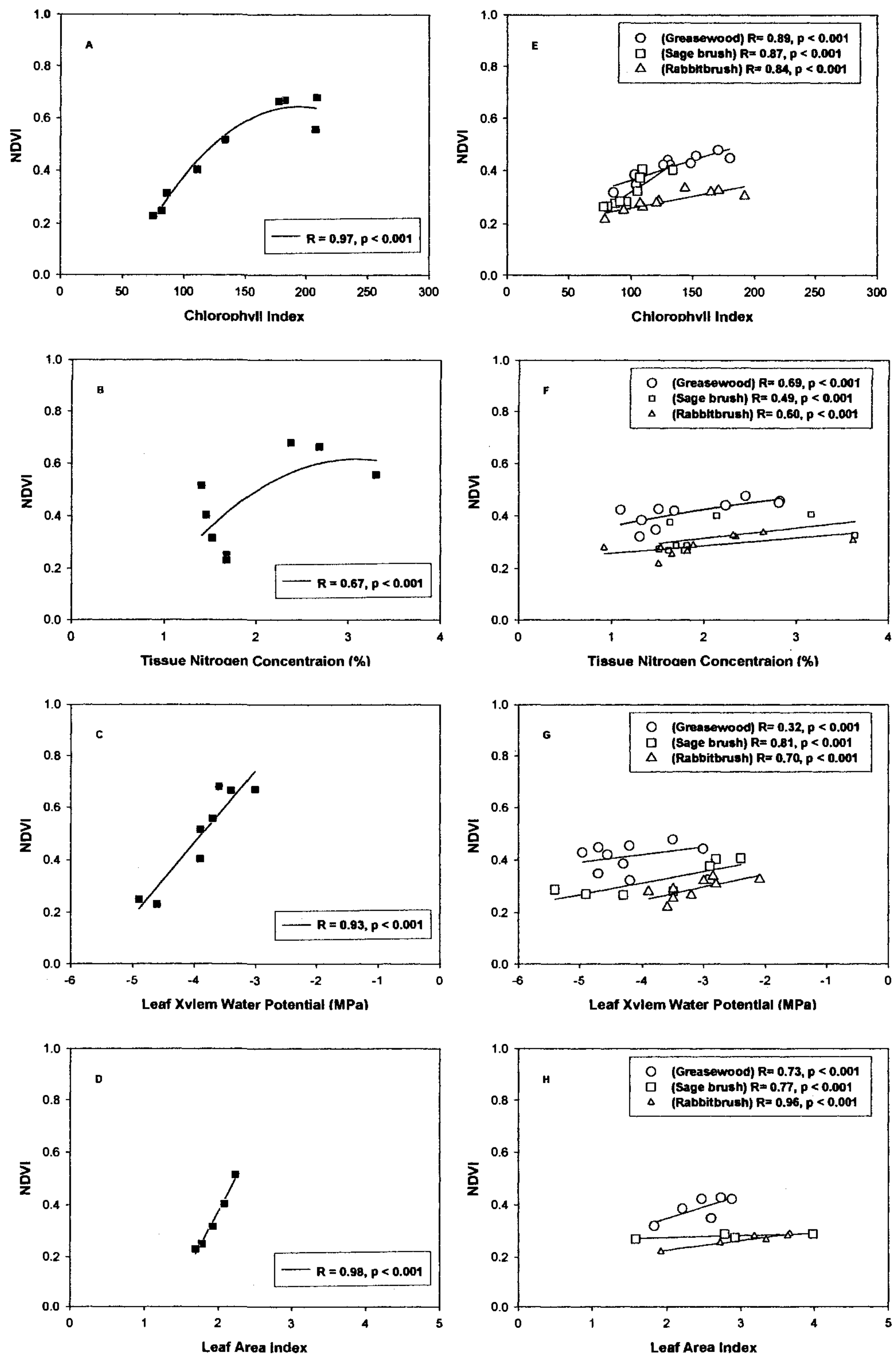

Figure 2-5. Comparison of plant measurements relationships with SKR-1800 NDVI values between the Snake Valley 1 site (left panel) and the Spring Valley 1 site (right panel).

NDVI and tissue moisture content were significantly correlated for sagebrush (*r* = 0.93, *P*<0.001) and rabbitbrush (*r* = 0.73, *P*<0.001). Whereas, a non significant correlation was observed between TM and greasewood NDVI (*r* < 0.35) at both sites (data not shown). At the SV1 site and the SNK1 site, greasewood TM values remained quite stable for the entire experimental period (May-September), (Figure 2-6). However, sagebrush and rabbitbrush TM values showed a consistent decline over time from values as high as 0.69% at the beginning of May to values as low as 0.45% and 0.35%, respectively by late September. Greasewood, a halophyte has succulent leaves, whereas the two other species are glycophytes with non-succulent leaves. Hence, greasewood TM values remained high and changed little over time (~0.75%). During the same period, greasewood NDVI values showed a steady decline between May and September (Figure 2-1, 2-2). Whereas, for sagebrush and rabbitbrush, TM and NDVI values followed the same temporal trend (Figure 2-3) resulting in significant correlations (*P*<0.001).

In all cases, no significant correlations were found between NDVI and Canopy-air temperature differentials $T_c - T_a$ as well as between NDVI and surface soil water content. TDR measurements did not show any clear or significant change in soil moisture content at various depths over time (data not shown). However, at the shallow surface (5 cm), soil moisture content responded at both sites to rainfall events.

<u>Relationship between ET_a and ground-based NDVI</u>

Total cumulative ET_a during the experimental period (May 5 to September 30) was 34.9 cm for the SNK1 site and 11.0 cm for the SV1 site (Table 2). This significant difference in ET was associated with significant differences in percent vegetation cover.

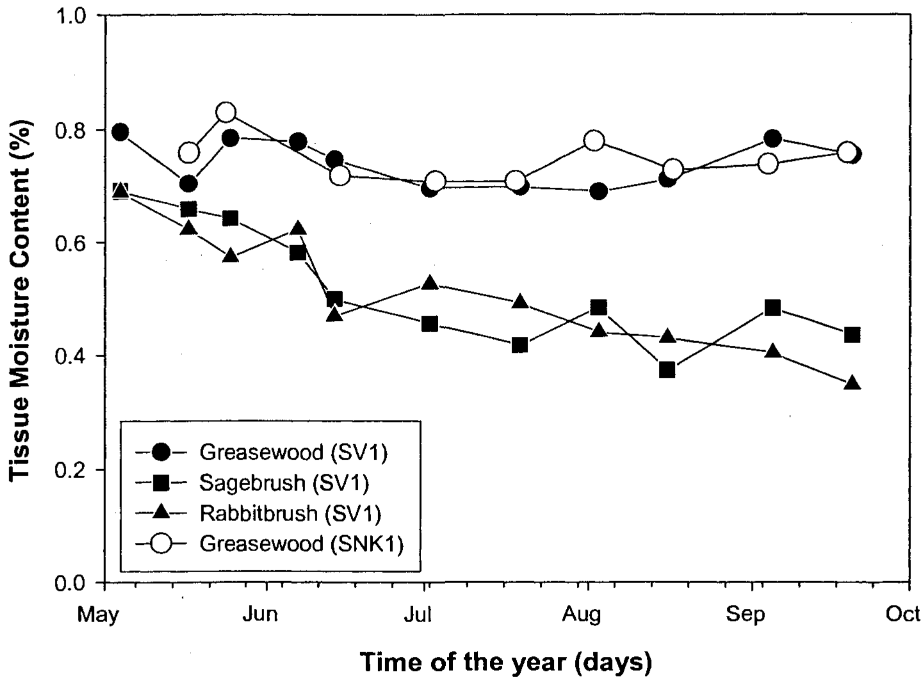

Figure 2-6. Leaf moisture content for greasewood, sagebrush and rabbitbrush.

Table 2. Major soil-plant and atmospheric characteristics of Spring Valley 1 site (SV1) and Snake Valley 1 site (SNK1).

Site*	ET_o (cm)	Rainfall (cm)	ET_a (cm)	Ground water depth (m)	Surface soil texture sand/silt/clay (%)	Canopy percent cover (%)¶
SV1	79.5	6.0	11.0	4.7 (SD:4.66 ± 0.05)	85.2 / 9 / 5.7	19.7
SNK1	84.8	6.2	34.9	5.0 (SD:5.0 ± 0.04)	42.6 / 34.9 / 23.1	54.9

ET_o: potential evapotranspiration; ET_a: actual evapotranspiration.
ET_o, ET_a and rainfall are cumulative totals, whereas, % cover is a one-time estimate taken during the early summer period.
**Data acquired during the experimental period from May 5 to September 30, 2007*
¶Percent cover data are from the center plot where the eddy flux towers are located.

At both sites, the occasional maximum ET values were associated with rainfall events. As shown in Figure 2-7, ET values at the SV1 site remained stable and low, showing only minimal fluctuations over time, inferring limited soil evaporation associated with the high sand content in the profile and low transpiration associated with the sparse vegetation at the site. However, in the case of the SNK1 site, ET values were consistently higher than the SV1 site showing a distinct separation between late-spring and early-summer (higher values) and late-summer (lower values). ET showed a distinct decline starting from the beginning of August, corresponding to a similar trend shown by greasewood NDVI values (SNK1: $r = 0.57$, $P < 0.001$). Although, it is difficult to compare or link eddy covariance ET flux measurements to a single and localized optical measurement from an individual canopy within the tower footprint, it was possible in this particular case to identify some similarities. The relationship between ET and NDVI at one site and not the other site was associated with differences in the vegetative surfaces, where greasewood represented the majority of the canopy cover at SNK1 but only 3% of the canopy cover at SV1.

<u>Comparing ground-based NDVI and satellite-NDVI</u>

For both sites, satellite NDVI values were lower than the ground-based NDVI values because the satellite synoptic view covered a surface area of 625 m^2 which represented the integrated optical properties of all surface components. Whereas, the ground-based NDVI values represented a single point measurement within an individual canopy or a bare soil surface. Satellite NDVI values were higher at the SNK1 site compared to the SV1 site (Figure 2-8A). At the SV1 site, Landsat-NDVI values more closely approximated the ground-based NDVI values for bare soil indicating that the percentage of exposed soil surfaces at this site (>80%) was the main driving force behind the low NDVI values (Figure 2-8B). However, at the SNK1 site Landsat-NDVI values revealed a subtle decline over time associated with a steep decline in greasewood NDVI values, indicating a more significant contribution from the high percentage of plant canopies at this site (54.9%) compared to the SV1 site (19.7%).

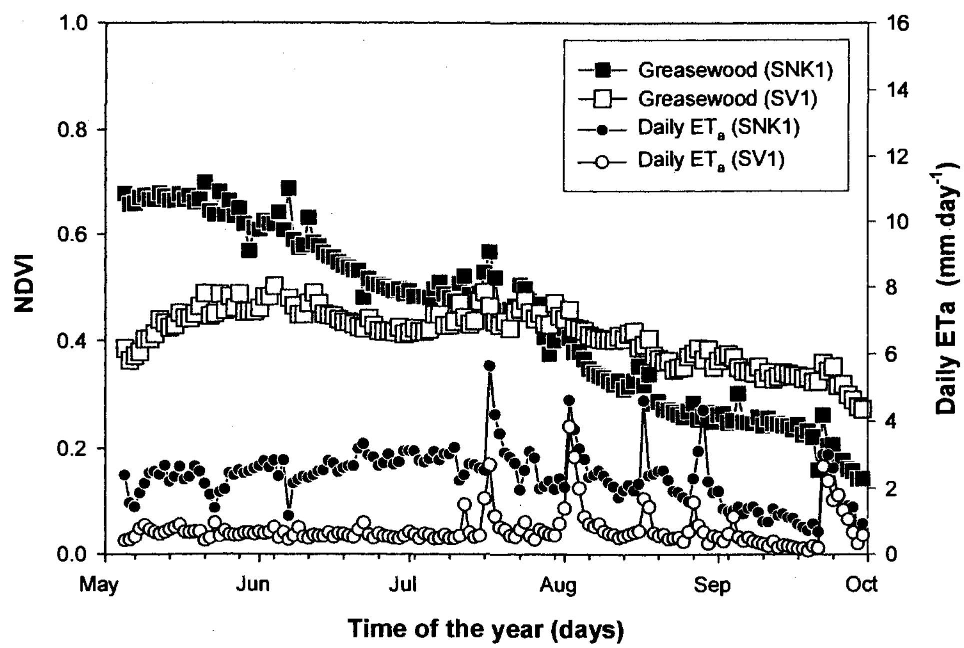

Figure 2-7. Average midday (11:30-13:30h) NDVI values and average daily ET_a values between May 5 and September 30, 2007.
Average midday NDVI values are both for a single greasewood plant from the Snake Valley 1 site (closed squares) and from the Spring Valley 1 site (open squares). Average daily ET_a values are from Snake Valley 1 site (closed circles) and from the Spring Valley 1 site (open circles).

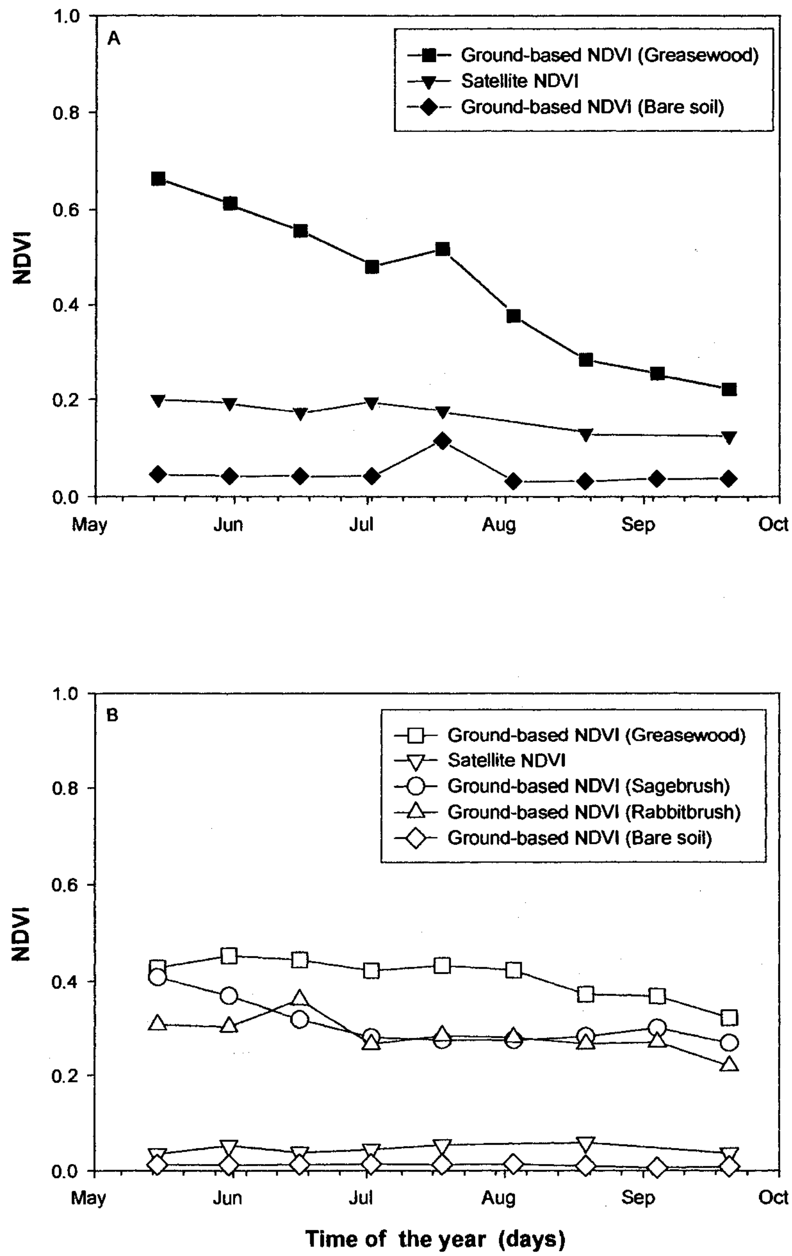

Figure 2-8. Comparison of ground-based NDVI values and Landsat-NDVI acquired during satellite overpasses.
Average midday ground-based NDVI values are for (A): greasewood and bare soil (closed symbols) from the Snake Valley 1 site and for (B): greasewood, sagebrush, rabbitbrush and bare soil (open symbols) from the Spring Valley 1 site. Landsat-NDVI values (closed inverted triangle) are from (A): Snake Valley 1 site and (open inverted triangle) (B): Spring Valley 1 site.

Discussion

The ability to assess NDVI at greater frequency and at finer spatial scales than satellite imagery is needed to develop stronger more robust data sets for further validation of satellite NDVI, vegetation growth and ET relationships. In this study a ground-based NDVI system was used to provide long term monitoring of phonological development and soil surface characteristics on a daily timescale at two different semi-arid environment settings, mainly characterized by having a dense versus sparse vegetation cover. NDVI data retrieved at the sparse vegetation site (SV1 site) during the period from January to November, 2007 provided detailed temporal information on the entire phenological cycle of greasewood allowing for clear distinction between different phenological stages and for clear identification of the length and the pattern of the active growing season (early April to late September). The seasonal pattern of NDVI phenology is somewhat similar to the one observed by Huemmrich *et al* (1999) using radiation sensors mounted on flux towers to measure daily NDVI above the canopies of a boreal forest.

The temporal differences in greasewood NDVI values between the SV1 and the SNK1 sites during the experimental period (May-September) indicated the ability of NDVI to distinguish between the response of the same species across space and over time based on the difference in the existing growing conditions at each site. The comparison of the NDVI time series indicated that SNK1 greasewood NDVI values were significantly higher ($P<0.001$) than SV1 greasewood NDVI values in the spring and early summer period during the active growth and canopy development phase and significantly lower ($P<0.001$) during the summer dry period associated with water limitations, indicating the impact of water availability on the growth and development of the same species. In this context, the discrepancy in the timing of greasewood spring green-up (two weeks delay at SV1) and early summer NDVI peak values between the two sites may be attributed to a favorable response of greasewood plants at the SNK1 site to greater soil moisture from storage after winter rainfall. Availability of this soil moisture early in the growing period associated with lower atmospheric demand would be expected to support faster and greater growth.

The edaphic data gathered during this study (Table 2) indicated the possible impact of soil texture variation on the growth characteristics of greasewood between the two sites. The high percentage of sand (>85%) in the soil profile at SV1 would lead to higher infiltration rates and to lower moisture holding capacity compared to the loamy soil at the SNK1 site. However, surface soil moisture measurements and tissue moisture content did not provide any clear indication of water stress during the summer dry down period as indicated by the steep decline in NDVI values, especially for the greasewood plant from the SNK1 site, which may partly be explained by the succulent morphology of greasewood leaves associated with its halophytic nature. On the other hand, even though greasewood is a phreatophyte and is capable of accessing ground water, the fact that leaf xylem water potentials declined below -5.0 MPa would suggest that ground water extraction was not great enough to offset summer stress. The results would suggest that greasewood at both sites relied more on the availability of surface soil moisture from winter rain and the occasional summer rainfall pulses (facultative phreatophyte). The depth of the water table at both sites was similar and changed little over the growing season.

NDVI time series of sagebrush and rabbitbrush from the SV1 site allowed for a clear distinction between the two species based on the difference in the peak and magnitude of the spring early-summer green-up phase (May- early June) and the rate and slope of the downward early winter adjustment phase (October-November). Such a distinction is not possible with satellite data or even with full range hyperspectral measurements (visible to NIR) especially when taken at one time or at different time intervals that do not coincide with key phenological changes during the growing season. The ability of NDVI to distinguish between different species is in accordance with the finding of Claudio *et al* (2006) for point measurements taken at a single time within the same area. Comparison of NDVI time series between greasewood, sagebrush and rabbitbrush from the same site (SV1) also allowed for retrieval of key time periods during the growing season when the NDVI time series exhibited very distinct patterns for each vegetation type. These key time periods were represented by the early green up period (May-June) with greasewood having higher NDVI values (Figure 2-1) followed by a green up period for sagebrush and then rabbitbrush (Figure 2-3). Additionally, the late summer dry down period (September-November), referred to as phase (IV) and phase (V) in this study, also represented key time periods with sagebrush having higher NDVI values and a lower slope followed by greasewood and then rabbitbrush both with lower NDVI values and steeper slopes.

Native desert shrub species in the Great basin have developed multiple strategies to cope with their environment. In this aspect, many species showed a great deal of variation in their rooting depths, phenology and response to drought stress (Hacke *et al.*, 2000). Greasewood, sagebrush and rabbitbrush are found to exhibit interspecific and intraspecific variation in water stress (Donovan & Ehleringer, 1994). Hacke *et al* (2000) classified rabbitbrush (C_3 photosynthetic pathway) under a "summer green" functional group with all shrubs under this category having shallow root system (< 2.5 m) and are able to sustain summer drought and maintain leaf area. However, rabbitbrush exhibits considerable leaf dieback in July and August (Sperry & Hacke, 2002). Greasewood which is a C_3 deciduous shrub, very tolerant to salt and alkali soils, has high root density close to the surface and large tap roots capable of reaching ground water up to 5.0 m (Donovan *et al.*, 1996). Greasewood also maintains high photosynthetic rates through the summer period, flower in mid-late summer and senesce in late fall (Donovan *et al.*, 1996). These characteristics related to phenology were also documented in our study.

Snyder *et al* (2004) found that in arid and semi-arid habitats summer rain pulses did not affect canopy growth of many desert species including greasewood and rabbitbrush. In our study, NDVI values showed an increase following rain event, indicating that the plants used summer water to improve plant water status and chlorophyll content as a short term physiological response that may not be connected to growth as this characteristic was not monitored.

Sagebrush (C_3 photosynthetic pathway) is known to be the dominant shrub species in the Great Basin capable of coping with its driest summers and coldest winters, and remains evergreen (Kolb & Sperry, 1999). In addition to being an evergreen shrub, sagebrush is known to have a semi-drought deciduous characteristic. In this case, the plant produces large ephemeral leaves on the elongating shoots during the spring period and abscises them during the summer dry period (Miller & Shultz, 1987). During the dry summer periods, sagebrush plants use hydraulic lift to transport water through their root system from deep to shallower soil layers to maintain transpiration (Donovan & Ehleringer, 1994). Hydraulic lift in sagebrush is usually coupled with maintaining phosphorus and nitrogen uptake, enabling the plant to continue nutrient uptake under low soil water potentials (Matzner & Richards, 1996). Sagebrush roots were found to be more vulnerable to cavitation than the stems during summer drought (Kolb & Sperry, 1999; Sperry & Hacke, 2002). However, sagebrush plants were found to benefit from water stored following summer rainfall pulses or over-winter recharge through uniform distribution of this water in the soil column by roots (Ryel *et al.*, 2004) resulting in plant physiological activities being maintained during drought periods.

NDVI time series analysis captured consistent phenological patterns for the different vegetation types, characterized by peak NDVI values during spring and the early summer period. This observation is in agreement with satellite observed NDVI peaks reported by Weiss *et al* (2004) for different semi-arid vegetation communities in New Mexico. The pronounced decline in NDVI values observed for all species during the late summer period associated with high temperatures and high atmospheric demand as well as depleted surface soil water indicated a response to water stress and drought conditions. Although NDVI is primarily an indicator of health and greenness and is more affected by loss of chlorophyll pigment and canopy color changes of drying plants, this does not exclude its relationship with plant water status, which has been reported in previous remote sensing studies (Peñuelas *et al.*, 1997; Claudio *et al.*, 2006). During the summer period, all vegetation at both sites showed a dynamic response to rainfall pulses translated into increasing NDVI values following these rainfall events. Based on past studies, the apparent response to summer precipitation is a common feature for vegetation in arid and semi-arid environments (Weiss *et al.*, 2004) indicating that this type of vegetation is highly sensitive to the temporal fluctuations in climatic conditions during its growing season. Additionally, not only did the time series of NDVI track the response to rainfall events during the summer period, but also showed a time lag in the responsiveness of each species, which is in agreement with previous work done by Schmidt & Karnieli (2000) to assess the seasonal variability of semi-arid vegetation using AVHRR-NDVI.

Soil NDVI time series produced a clear distinction between the loamy soil (SNK1 site) and the loamy sand soil (SV1 site), indicating the ability of NDVI to distinguish between various desert soils based on color and wetness (Figure 2-4). NDVI captured the difference in surface moisture properties between the two soil types throughout the growing season and how they responded to summer rainfall pulses. The consistent lower NDVI values for the loamy sand soil especially indicated that soil moisture was virtually absent at the surface layers because it quickly infiltrated to deeper horizons following rainfall, causing the soil to dry out more rapidly through the process of redistribution and evaporation. Conversely, the loamy soil at the SNK1 site held moisture at the surface, maintaining higher moisture contents in the top layers for a longer period following precipitation, as reflected in the soil NDVI values (Figure 2-4). The ability of NDVI to distinguish between different vegetation and soil types provides a solid rationale for using this vegetative index to help partition semi-arid landscapes into vegetation and bare soil to monitor such parameters as growth, stress and surface energy fluxes.

Samson (1993) suggested that the shape and the magnitude of the seasonal NDVI curve can be used to identify the type of vegetation cover. This may hold true for dense forested areas with specific types of deciduous or evergreen trees, making it easier to distinguish between unchanging NDVI values for evergreen trees versus changing NDVI values for deciduous trees, especially between distinct phases of green-up and senescence. However, applying such an analogy to semi-arid regions characterized by a high degree of surface heterogeneity can be problematic. Thus, further validation steps in the form of long term monitoring studies are needed to establish an acceptable degree of consistency with regard to the temporal pattern of NDVI time series for each species. In this context, the calculated area under the curve generated a single value for each NDVI time series curve but did not provide any information with regard to differences in phenological stages or type of fluctuations that occur throughout the season in response to climatic conditions. The value of having the integral of the NDVI time series curve can only be appreciated by developing long term monitoring studies and retaining such information over time for each species.

Most NDVI time series studies reported in the literature have been mainly based on monitoring the seasonal and inter-annual patterns of land cover type using an AVHRR sensor to track changes in phenology (Weiss *et al.*, 2004; Hermance *et al.*, 2007). Such studies used weekly or biweekly composited AVHRR-NDVI over several years. Although the reported results indicated the reliability of using AVHRR derived NDVI time series to observe seasonal and annual trends in vegetation cover, it is clear that there are numerous difficulties associated with using AVHRR-NDVI to provide continuous and accurate analysis of plant phenology, especially within environmental settings where soil and land characteristics are the major driving forces influencing the NDVI values generated at the pixel level. Some of these problems were reported by Huemmrich *et al* (1999) and included cloud cover contamination, coarse temporal resolution (especially when the data are not acquired daily) and coarse spatial resolution (1 km × 1 km) making it difficult to compare AVHRR data with field observations. The ground-based NDVI sensor we used in this study overcomes most of the problems associated with the coarse temporal and spatial resolution of satellite systems allowing for daily monitoring of vegetation and soil characteristics at high resolution.

Landsat images provided NDVI values on a per pixel basis (25 m × 25 m). Our data showed that NDVI values were higher at the SNK1 site than at the SV1 site (Figure 2-8) due to the difference in percent vegetation cover between the two sites thus indicating the influence of the reflectance from bare soil surfaces on the integrated NDVI value. However, satellite data did not provide any potential discrimination between soil and vegetation types or characteristics that differentiate the two sites. Furthermore, the subtle changes in the optical properties of surface soil and vegetation (as they responded to rainfall events) observed with the ground-based NDVI system throughout the growing season were not apparent in the coarse spatial and temporal resolution of the satellite data. This was especially true for the different phases of vegetative growth observed between the two sites and within the SV1 site. Ground-based NDVI systems are a more robust tool that can be used to monitor and track the spatial and temporal variability of species composition, phenology and growing characteristics with greater detail, not possible with satellite-based NDVI systems. However, challenges do exist with scaling such data.

The significant correlations between NDVI and plant parameters measured in this study indicate the utility of VIs to predict and relate to many physiological processes over time (Figure 2-5) especially to chlorophyll index indicating the tight relationship between

NDVI and chlorophyll content as reported by Baghzouz *et al* (2007). The difference in the correlation of greasewood NDVI and plant parameters between the SV1 site and the SNK1 site shows that these types of relationship can be site specific and may be good indicators of the existing growing conditions that differentiate sites on a spatial scale.

At the SNK1 site, the difference between the green-up and the dry down period of greasewood as demonstrated with NDVI, was shown to be somewhat sensitive to changes in evapotranspiration on a daily basis (Figure 2-7) despite the difference in scale between the two measurements (single canopy vs. flux tower footprint). This finding can be explained in part by the uniformity of the SNK1 site in terms of species composition (one single dominant species) and the high percentage of vegetation cover (>54%). However, at the SV1 site such a trend did not exist, suggesting that in areas with sparse vegetation and multiple species, changes in daily NDVI of one species will not adequately reflect ET on a mixed stand level basis.

The difference in growth characteristics of the same species between sites and between different species within the same site may explain some of the spatial distribution of surface fluxes associated with semi-arid environments. The magnitude of green-up and duration of active growth and senescence phases for the different species can be different from one year to another based on variations in prevailing weather and resultant soil moisture availability. Thus, further monitoring and long term inter-annual observations are needed for other sites in the Great Basin that have different soil and /or vegetation types. As more ground-based NDVI data becomes available, it can be used to provide a more meaningful linkage between surface energy fluxes and remotely sensed observations at multiple scales, especially when data are combined across different sites and across multiple years. Such an approach based on long term monitoring could prove to be extremely valuable in predicting possible impacts of changing climatic conditions and ground water fluctuations on the dynamics of vegetation growth in this region.

In summary, based on the performance of the NDVI sensors in this study, this instrument was shown to be a powerful tool in providing unattended daily monitoring of soil and vegetation optical properties in two different semi-arid environmental settings. NDVI collected on a daily basis provided discrimination of phenological characteristics between different vegetation types throughout an entire growing season and was able to track small and subtle changes in vegetation development not possible with satellite imagery. The NDVI data set also allowed for detailed comparison between the two contrasting classes of soil texture that differentiate the sites, which we believe is an essential factor controlling the growing patterns between the two sites. Based on the findings of this study, an approach to scale NDVI from single canopies and bare soil surfaces to an integrated satellite pixel NDVI basis within the footprint of the eddy flux towers is being undertaken employing the percent cover data for each species as a weighting factor (Chapter 3).

Acknowledgments

The study was conducted as part of the Great Basin evapotranspiration project funded by Southern Nevada Water Authority (SNWA). We thank the entire field and lab team in Dr Devitt`s lab at the University of Nevada Las Vegas for their hard and efficient work. We are also grateful to Brian Bird for his help with data acquisition.

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CHAPTER 3

ASSESSMENT OF GROUND NDVI METHODS AND EVAPOTRANSPIRATION ESTIMATION FROM SATELLITE DATA IN TWO SEMI-ARID GREAT BASIN SETTINGS

Introduction

The Southwestern region of the United States has limited renewable water resources and is experiencing an unprecedented and extended period of drought. Southern Nevada's population growth has forced local water agencies to look for other alternative sources to move toward a more sustainable state. In 2004, the Southern Nevada Water Authority (SNWA) applied for water rights in East-central Nevada basins with the intent of building pipelines to remove and transport 222,026,760 m^3 of groundwater per year to urban areas in Southern Nevada to be used for commercial, household, recreational and entertainment purposes (Nevada water use issues, 2006). Transferring thousands of acre feet of water per year from distant remote basins can come with environmental and socio-economic costs. Consequently, developing a scientifically sound approach to accurately estimate the hydrologic budget of these basins is needed to assess future cumulative impacts on the region's environment.

Terrestrial evapotranspiration (ET) defined as the evaporation of water from soil surfaces and transpiration from plants (Monteith & Unsworth, 1990), is the major component associated with the hydrological cycle after precipitation in arid and semi-arid regions. Depending on the geographical location and the season, ET varies with prevailing meteorological conditions; especially net solar radiation, wind speed, precipitation and temperature. Furthermore, in agricultural lands and naturally vegetated areas, ET rates are also affected by topography and by land surface characteristics such as soil texture, soil moisture, depth of ground water, vegetation type and density. In this context, when water supplies are limited, accurate estimations of ET over large scales of agricultural and natural ecosystems are crucial for addressing water related management issues such as water rights and allocations, irrigation planning, management and distribution (Chehbouni *et al.*, 2008; Singh *et al.*, 2008).

Harrold, 1969 (in Van Hylckama, 1975) estimated that 75% of annual precipitation in the conterminous United States is lost as evapotranspiration and this percentage can reach up to a 100% in arid zones. In semi arid regions where phreatophytes are abundant, ET is closely linked to ground water level and discharge (Steinwand *et al.*, 2006). In this regard, Goodrich *et al* (2000) also indicated that ground water recharge is highly impacted by ET in semi-arid regions, especially during periods of extended drought when surface snowmelt is absent. Thus, ET is considered as the main component of the discharge process in hydrologically closed basins, like many found in the Great Basin region of East-central Nevada, where recharge is mainly from precipitation. On the other hand, the spatial dynamics and heterogeneity of semi-arid environments in terms of the variability in plant density, species composition, distribution and growing conditions, represent a very challenging task in studying surface energy fluxes like ET. This task becomes even more difficult, especially when trying to partition

ET into soil and plant components over areas of sparse canopy cover as the relative contribution of these two components to ET can vary daily and seasonally (Massman & Ham, 1994). According to Portoghese *et al* (2008), part of this problem is related to the strong interconnections between the spatial heterogeneous nature of climate, soil properties and vegetation dynamics associated with semi-arid landscapes.

Until recently, ET measurements were confined to relatively small foot prints around meteorological stations, providing limited spatial coverage. Application of remote sensing technology has been shown to be the only feasible and most efficient way to monitor and estimate ET over regional and global scales. Over the last few decades, a number of studies have focused on combining remote sensing and ground-based meteorological measurements and weighing lysimeters to estimate ET over limited small areas in semi-arid regions (Jackson *et al.*, 1983; Reginato *et al.*, 1985; Moran *et al.*, 1989). In more recent years, a growing body of research has focused on using satellite-based remote sensing data to estimate ET over larger areas (Laymon *et al.*, 1998; Loukas *et al.*, 2005; Nagler *et al.*, 2005a, 2005b; Batra *et al.*, 2006; McCabe & Wood, 2006; Wang *et al.*, 2007; Singh *et al.*, 2008).

Remote sensing-based approaches used to estimate ET vary in their input criteria and complexity from simple statistical or semi-empirical methods to more complex physically-based analytical and numerical simulation models. Most of these methods were reviewed and evaluated by Moran & Jackson (1991), Kustas & Norman (1996), Courault *et al.* (2005) and Gowda *et al.* (2007), while Glenn *et al.* (2007) reviewed the progress and the current state of ET estimation research using remote sensing and ground measurement methods.

Essentially, most remotely-sensed ET estimation models rely on using vegetation indices, with the Normalized Difference Vegetation Index (NDVI) as the most frequently used vegetation index. Vegetation indices have been shown to be near-linearly related to photosynthetically active radiation (PAR) absorbed by a plant canopy, and therefore to light dependent processes such as photosynthesis, which is based on light absorption by chlorophyll (Glenn *et al.*, 2008). ET rates are also linked to plant photosynthetic activity and transpiration because carbon and moisture fluxes are largely controlled by water and carbon exchange at the scale of the leaf stomata (Sellers *et al.*, 1997). In this context, NDVI was used to estimate ET based on the strong correlations between ET and NDVI that have been reported by numerous studies (Loukas *et al.*, 2005; Nagler *et al.*, 2005a, 2005b, 2007; Glenn *et al.*, 2008)

Despite the promising results obtained from using remote sensing technology in evapotranspiration research, often there is an apparent discrepancy between the spatial and/or the temporal resolution at which most of the existing satellite platforms operate and the practical scale at which ecosystem processes are represented (McCabe & Wood, 2006). Such problems increase the level of uncertainty in relating remote sensing data to the footprint of ET towers without a certain degree of validation. In fact, flux tower measurements were considered as ground-truth data that can be used to validate remote sensing data and simplify the scaling process of plant related processes over wide areas (Glenn *et al.*, 2007, 2008). However, simple and direct extrapolation of ET measurements from a finer scale within the eddy flux towers footprint to the satellite coarser resolution scale represents a drawback for obtaining accurate ET estimations without further ground truth or validation data. Thus, scaling ET over broad areas and over time remains a challenging task mainly because of the complexity and uncertainty of obtaining a working model that combines related biophysical processes operating at various spatial and temporal scales. Some studies have used high resolution IKONOS imagery to scale CO_2 flux measurements to 1 km^2 around the flux tower (Kim *et al.*, 2006) or a combination of multiple satellite sensors (McCabe & Wood, 2006) to bridge the gap between the ET tower flux footprint and the (Moderate Resolution Imaging Spectrometer) MODIS kilometer-scale. However, comparison of surface flux and ecosystem processes estimates from different satellite sensors showed that cross-scaling can become an issue due to the inconsistency in the final product of the high resolution and coarse resolution sensors influenced by surface heterogeneity (Cheng *et al.*, 2006; McCabe & Wood, 2006).

In more recent years, the scientific community has realized the need to improve the accuracy and simplicity of ET-remote sensing based models to enhance our understanding and interpretation of satellite-data-based products. Efforts have been geared toward repeatable field sampling methods using automated tower-based spectral data collection systems like the one developed by Gamon *et al* (2006a) as part of the SpecNet (spectral network) group (Cheng *et al.*, 2006; Claudio *et al.*, 2006 ; Gamon *et al.*, 2006b; Hilker *et al.*, 2007). The aim of this new effort has been to accurately depict key ecosystem processes at a scale not usually captured by current remotely sensed observations.

In this study, a more intensive and long term field analysis was undertaken to acquire spectral information compared to previous research. The primary objective was to present a simplified approach for improving ET estimation and scaling NDVI based on the integration of various remote sensing sensors with different spectral, spatial and temporal resolutions to generate and compare NDVI values from sparse and dense vegetation settings in the Great Basin. The trend of NDVI values generated from hyperspectral transect measurements acquired within footprint of the eddy flux towers and continuous daily NDVI values generated from a ground-based NDVI system mounted on site-specific soil and vegetation components were examined, to provide a meaningful interpretation of the mixed Landsat 5 TM derived NDVI signature. The presence of two different sites with different species composition and density provided an excellent opportunity to investigate the main factors influencing ET and NDVI variations at various scales during the active growing season in a semi-arid environment.

Materials and methods

Study site description

The Great Basin is a cold desert with a total area of over 650,000 km^2 located in the intermountain U.S. It contains over 500 N-S trending mountain ranges with elevations reaching to over 4,000 m (Chambers & Miller, 2004). Inputs of rivers and streams from the surrounding mountains supply water to over 70 basins of diverse topography (Chambers & Miller, 2004). The climate is characterized by warm, dry summers and cold winters, with most precipitation falling as snow in the winter months. The vegetation type and density varies with precipitation patterns, soil type and water movement, with vegetative growth most abundant where ground water is close to the surface (Laymon *et al.*, 1998).

The study was conducted during the growing season of 2007 from May to September in two contrasting sites in the Great Basin. The sites were selected based on the difference in vegetation cover, species composition and soil type (Figure 1). Spring Valley 1 site (SV1) was located at 38° 46' 32.79" N and 114 ° 28' 7.65" W, with an elevation of 1761.6 m above sea level. The site has a sparse vegetation cover with a mixture of species that include greasewood (*Sarcobatus vermiculatus)*, rabbitbrush (*Chrysothamnus viscidiflorus*) and shadscale (*Atriplex corifertifolia*), with the dominant species being big sagebrush (*Artemisia tridentata*). Snake Valley 1 site (SNK1) was located at 38° 41' 51.98" N and 114 ° 5' 19.32" W, with elevation of 1684.9 m above sea level. The SNK1 site has a dense and uniform phreatophytic cover dominated by *Sarcobatus vermiculatus*. Soil texture analyzed prior to the beginning of the study indicated that the SV1 site at the surface was a loamy sand (85.2% sand), while the SNK1 site at the surface was classified as a loamy soil with smaller amounts of sand (42.6%) and higher amounts of silt (34.9% vs. 9%) and clay (23.1% vs. 5.7%) compared to the SV1 site. In order to monitor ground water levels, a monitoring well was installed at a depth of 22.86 m at the SV1 site and at a depth of 11.58 m at the SNK1 site. Ground water depth measurements were recorded and monitored using a submersible HOBO hydrostatic transducer (Onset Computer Corp, Bourne, MA, USA) paired with a miniature data logger system (HOBOware Pro 2.3.1). Measurements obtained before the start of the study revealed a ground water depth of 4.7 m at the SV1 site and 5.0 m at the SNK1 site.

Percent vegetation cover

Detailed field measurements of species composition and total percent cover were obtained at each site during the growing season. At the SV1 site, percent cover measurements were acquired for the center plot and for four additional plots surrounding the center plot (North-South and East-West directions). Whereas, at the SNK1 site, measurements were only obtained for two plots (center plot and an adjacent plot to the south) because of the uniformity of the site. Each 25 m by 25 m plot was divided into 25 strips (25 m long and 1 m wide) and species were identified and counted along each strip and then totaled for the plot. At the same time, the height and diameter of every green and dead plant was measured and the green portion of each canopy was estimated visually. Canopy area was then calculated for each species based on the formula of an ellipsoid and total percent vegetation cover was estimated for each plot.

Micrometeorological and ET measurements

At each site, an eddy flux tower (Campbell Scientific, Logan, UT, USA) was installed at a central location within measurement plots of 625 m^2 each. Fetch in all directions was estimated in kilometers, easily exceeding the minimal standard of 100 times sensor height at both locations (Rosenberg *et al.*, 1983). 3D sonic anemometer (CSAT3, Campbell Scientific, Logan, UT, USA) along with an open path infrared gas analyzer (IRGA- Licor Biosciences, Lincoln, NE, USA) were mounted at 1 m height above the canopy to measure water and CO_2 fluxes at each site. ET towers rely on measuring the vertical components of wind speed at a single point over a canopy (Glenn *et al.*, 2008). The predominant wind direction changed from the north during the winter to the south during the summer. The 3D sonic anemometer and the IRGA were repositioned during early spring to point into the direction of prevailing wind to adjust for the seasonal change in wind direction.

All flux measurements were recorded at a sampling frequency of 10Hz and stored in a CR5000 data logger (Campbell Scientific). The final stage of flux analysis and calculations was accomplished using the EdiRe software (University of Edinburgh, Scotland, UK) developed by Clement & Moncreif (1999). Standard corrections were made following the protocol outlined by AmeriFlux (Lee *et al.*, 2004). Surface energy balance was calculated using the following equation:

$$R_n = G + H + LE \qquad (1)$$

Where, R_n is net radiation, G is soil heat flux, H is sensible heat flux and LE is latent heat flux (all units are W m^{-2}). Net radiation was measured with a NR-LITE-L net radiometer (Campbell Scientific) placed 3 m above the canopy, while soil heat flux was measured with an HFP01SC-L soil heat plates (Campbell Scientific) placed 8 cm beneath the soil surface. To obtain ET, latent heat flux values were divided by the latent heat of vaporization of water.

In addition to eddy covariance towers, a fully automated weather station (Campbell Scientific) was installed at each site to measure wind speed, wind direction, air temperature, relative humidity, solar radiation, and precipitation data, on an hourly and daily basis. In order to assess the relative environmental demand during the growing season, potential evapotranspiration estimated from a hypothetical grass reference of 0.12 m height was calculated from a set of meteorological variables using the Penman-Monteith equation (Monteith & Unsworth, 1990).

Remotely sensed measurements

Landsat data

During the 2007 growing season, 11 georectified Landsat 5 TM scenes of the two study sites acquired at approximately 16 days interval were purchased from the U.S. Geological Survey-Earth Resources Observation and Science (USGS-EROS) data center. Acquisition dates included April 13, April 29, May 15, May 31, June 16, July 2, July 18, August 3, August 19, September 4 and September 20. Calibration and empirical line atmospheric correction method (ELM) were conducted using ENVI image processing software (Research Systems, Inc., Boulder, CO, USA). Reflectance data from pre-processed cloud free Landsat images were then used to compute NDVI using band 3 (red: 630-690 nm) and band 4 (NIR: 760-900 nm):

$$NDVI = (\rho_{NIR} - \rho_{Red}) / (\rho_{NIR} + \rho_{Red}) \quad (2)$$

where ρ_{NIR} and ρ_{Red} are the spectra reflectance within the near-infrared and red band, respectively. Landsat-NDVI values were extracted for the center plot where the eddy flux towers were located (e.g., a single pixel) and from 25 pixels (25 m × 25 m each) surrounding the center pixel, and from 25 pixels south of the center pixel.

Ground-based NDVI measurements

Ground- based NDVI measurements were carried out using a dual channel SKR-1800 radiometer (Skye instruments LTD, Powys, UK) that simultaneously measures incident solar radiation and upward reflectance. The SKR-1800 radiometer was customized by the manufacturer to acquire data in two broadband channels comparable with Landsat 5 TM band 3 (red) and band 4 (NIR). NDVI sensors (upwelling and downwelling) were mounted at the SVI site above individual plant canopies of greasewood, rabbitbrush, sagebrush, and above an undisturbed bare soil surface. At the SNK1 site, the sensors were mounted above a greasewood canopy and an undisturbed bare soil surface. In all cases the field of view (FOV) was 25° and the height of the downward looking sensor was adjusted based on the size of the monitored plant so that the whole FOV represents only the shrub canopy. The ground-based NDVI sensors were installed within an adjacent 625 m^2 plot east of the center plot at the SVI site and within an adjacent 625 m^2 plot north of center plot at the SNK1 site. NDVI data were acquired every minute on a daily basis for the entire experimental period from May to September, 2007 and stored in a removable SM4M storage module (Campbell Scientific). All downloaded data were processed and NDVI was calculated based on the following equation (only average midday NDVI values (11:30 to 13:30 h) were used):

$$NDVI = \frac{(Z^* NIR_{R(nA)} * Y) - (Red_{R(nA)} * X)}{(Z^* NIR_{R(nA)} * Y) + (Red_{R(nA)} * X)} \qquad (3)$$

where,

X: NIR_I incident reading (μmol $s^{-1}m^{-2}$)

Y: Red_I incident reading (μmol $s^{-1}m^{-2}$)

Z: Ratio sensitivity of reflected NIR: Red

$NIR_{R(nA)}$: Reflected reading in nanoamps

$Red_{R(nA)}$: Reflected reading in nanoamps

Transect measurements

In order to create an integrated NDVI response from ground measurements, that is representative of a single Landsat pixel, the feasibility of using spectral reflectance measurements within flux tower transects as ground truth data was tested. During the experimental period from May to September of 2007, hyperspectral reflectance data were taken within the flux tower footprint at both sites. Transects were established using a 1 m interval marked rope and set upwind to correspond with the eddy flux footprint. Spectral reflectance data were collected using a PP Systems Unispec hand-held spectroradiometer (PP Systems, Amesbury, MA, USA) which operates in the range of 310 to 1130 nm with a sampling interval of 1 nm and 25° FOV. Measurements were taken manually by walking along the transect line and recording the spectral signature of each encountered target on a 1 meter interval. All measurements were taken at a relatively consistent height by maintaining the Unispec fiber tip at shoulder height. Reflectance readings were taken under clear skies around solar noon (11:00-14:00 h) to coincide with the Landsat 5 TM acquisition time and to avoid cloud effects. Prior to every transect run, the spectroradiometer was calibrated and standardized using a spectralon reference panel.

Transect measurements were taken twice during the experimental period. The first measurements were taken on July 2 (SV1) and on July 3 (SNK1) to coincide with peak vegetation growth and development. The second measurements were taken on September 19 (SNK1) and on September 20 (SV1) at the end of field data collection to coincide with the dry down period. On July 2 and July 3, transect sampling was conducted along a 50 m length in the East-West direction and along a 50 m length in the North-South direction. While on September 19 and September 20, transects were set at 25 m in a West-East direction and at 25 m in a North-South direction. Reflectance data measured every 1m along each transect was resampled to Landsat-5 TM red and NIR bandwidths using an ENVI (Research Systems, Inc., Boulder, CO, USA) subroutine. The resulting resampled data was then used to calculate NDVI as in equation (2).

Weighting ground-based NDVI

Ground-based NDVI time series measurements from individual shrubs taken with the SKR-1800 radiometer within a 25 m by 25 m plot were weighted over the periods of satellite overpasses between May and September using percent cover data of each plant and bare soil. Percent cover values for each species and for bare soil surfaces were adjusted based on the percent change in NDVI values recorded over time. In this case percent soil cover increased proportionally to the decrease in plant cover and NDVI. These adjusted percent cover areas of each species were then multiplied by the species NDVI values and then summed along with the bare soil fraction. The new weighted NDVI values were then compared with the integrated Landsat NDVI values. A predicted Landsat NDVI value was computed for each site using the following expressions:

$$NDVI_{SV1} = [NDVI_{GW} * (total\ GW\ \%\ green\ cover) + NDVI_{SB} * (total\ SB\ \%\ green\ cover) + NDVI_{RB} * (total\ RB\ \%\ green\ cover) + NDVI_{bare\ soil} *(total\ soil\ \%\ cover)] \quad (4)$$

$$NDVI_{SNK1} = [NDVI_{GW} * (total\ GW\ \%\ green\ cover) + NDVI_{bare\ soil} *(total\ soil\ \%\ cover)] \quad (5)$$

Where $NDVI_{GW}$, $NDVI_{SB}$, and $NDVI_{RB}$ are the ground-based NDVI values of greasewood, sagebrush and rabbitbrush, respectively.

Photosynthetically active radiation measurements

A Licor LI-190SA quantum sensor (Licor Biosciences, Lincoln, NE, USA) that measures incident photosynthetic active radiation (PAR) in the 400 nm and 700 nm waveband was mounted at each site to collect data every minute to a removable SM4M storage module (Campbell Scientific).

Data processing and statistical analysis

Soil-plant-atmospheric parameters were monitored during the course of the study to assess the relationship between ET and a satellite derived vegetation index. In particular, to determine to what extent these variables could be used to enhance ET-NDVI relationships within heterogeneous semi-arid environmental settings. Net radiation (R_n), air temperature (T_a) and PAR data measured during the process of this study were plotted against ET and NDVI over time to test for significant correlations and similar patterns. Multiple linear and stepwise regression analyses were used to account for the greatest amount of variation in the prediction of ET using SigmaStat version 3.1 (SPSS Inc, Chicago, IL, USA). Simple linear regressions were also established for each independent variable between and across the two experimental sites. All possible correlations were tested for significance at *P*-values ≤ 0.05 and for multicollinearity and autocorrelation problems. In all cases, prediction equations were accepted only if the variance inflation factor (VIF) of individual predictors was <2, the $\sum$VIFs for all predictors was <10 and the Durban-Watson test values were ≤ 2.5.

Results

Vegetation cover estimates

Vegetation cover at the SV1 site was sparse (total average ~ 17.5%) with sagebrush representing the dominant species (~ 68% of the total average vegetation cover) and greasewood the least dominant (~ 14% of the total average vegetation cover; Table 3). At the SNK1 site, vegetation cover was relatively dense (total average ~ 63%) with greasewood representing the dominant species (~ 97% of the total average vegetation cover). Other species represented a very small percentage (between 0.02% and 0.34%) of the overall species composition. In particular, annuals were encountered in some of the plots and not in others, as percent cover estimates were obtained over an extended period and the presence of annuals often coincided with the period during which the measurements were taken.

Transect NDVI

The SNK1 site showed a higher number of vegetation spectra than soil spectra compared to the SV1 site, reflecting the difference in vegetation cover between the two sites. At the SNK1 site, most of the vegetation spectra exhibited a similar shape, reflecting the uniform stand of greasewood (Figure 3-1A). However, at the SV1 site vegetation spectra exhibited different shapes, indicating a heterogeneous species composition (Figure 3-1B). Soil spectral curves were also clearly distinct in shape and magnitude between the two sites. The loamy sand soil from the SV1 site showed a lower reflectance response in both visible and near-infrared regions of the electromagnetic spectrum than the loamy soil from the SNK1 site.

Table 3. Summary of percent cover data for the two study sites.

Plants [a]	number of plants		% cover		% of bare soil	Total % of vegetation cover [b]
	Green	Dead	Green	Dead		
plot 1 (SV1)					86.15	13.85
GW	14	3	1.6	0.2		
SB	323	97	8.9	1.6		
RB	55	12	0.6	0.08		
plot 2 (SV1)					84.79	15.21
GW	41	6	5.3	0.4		
SB	172	78	4.5	1.4		
RB	113	46	1.9	0.6		
plot 3 (SV1)					79.46	20.54
GW	17	4	0.8	0.05		
SB	311	112	13.6	2.2		
RB	330	31	3.5	0.3		
plot 4 (SV1)					81.88	18.12
GW	16	1	1.02	0.02		
SB	312	48	12.9	0.9		
RB	361	6	3.0	0.1		
center plot (SV1)					80.31	19.69
GW	25	6	2.2	0.2		
SB	286	25	12.7	0.7		
RB	205	4	2.9	0.06		
plot 1 (SNK1)					28.89	71.11
GW	436	115	55.4	14.0		
center plot (SNK1)					45.07	54.93
GW	608	84	46.7	5.9		

This difference can be attributed to various soil surface characteristics that differentiate the two sites such as texture (85.2% sand (SV1) vs. 42.6% sand (SNK1)), color (SV1 10YR 7/2 Light Grey, SNK1 10YR 6/3 Pale Brown) as well as the availability of moisture at the surface. Additionally, within each plot various combinations of ground surface constituents and backgrounds such as dead branches, shrub shadows and litter were also encountered along these transects. The shape of their spectral reflectance curve can be easily distinguished from those of traditional bare soil and individual stands of vegetation.

During this period of the growing season (July 2 and July 3) associated with peak growth, the dynamics in vegetation greenness were clearly depicted by many key regions of the greasewood spectral reflectance curves. In particular, very low red reflectance (around 680 nm), and steep red edge slopes (around 700 nm) were observed, both influenced by high chlorophyll absorption, and very pronounced water troughs (around 970 nm) influenced by leaf moisture content (Figure 3-1). It is worth noting that during the dry-down period toward the end of the growing season (September), some of these spectral features either changed (red edge slope) or disappeared (water trough) in response to high temperatures and drought conditions (not shown).

The spatial patterns in NDVI were associated with different vegetation covers (sparse vs. dense) with different dominant vegetation types (Figure 3-2). While, the temporal patterns within sites are attributed to the variations in phenological stages between early July and late September driven by species type and environmental variables.

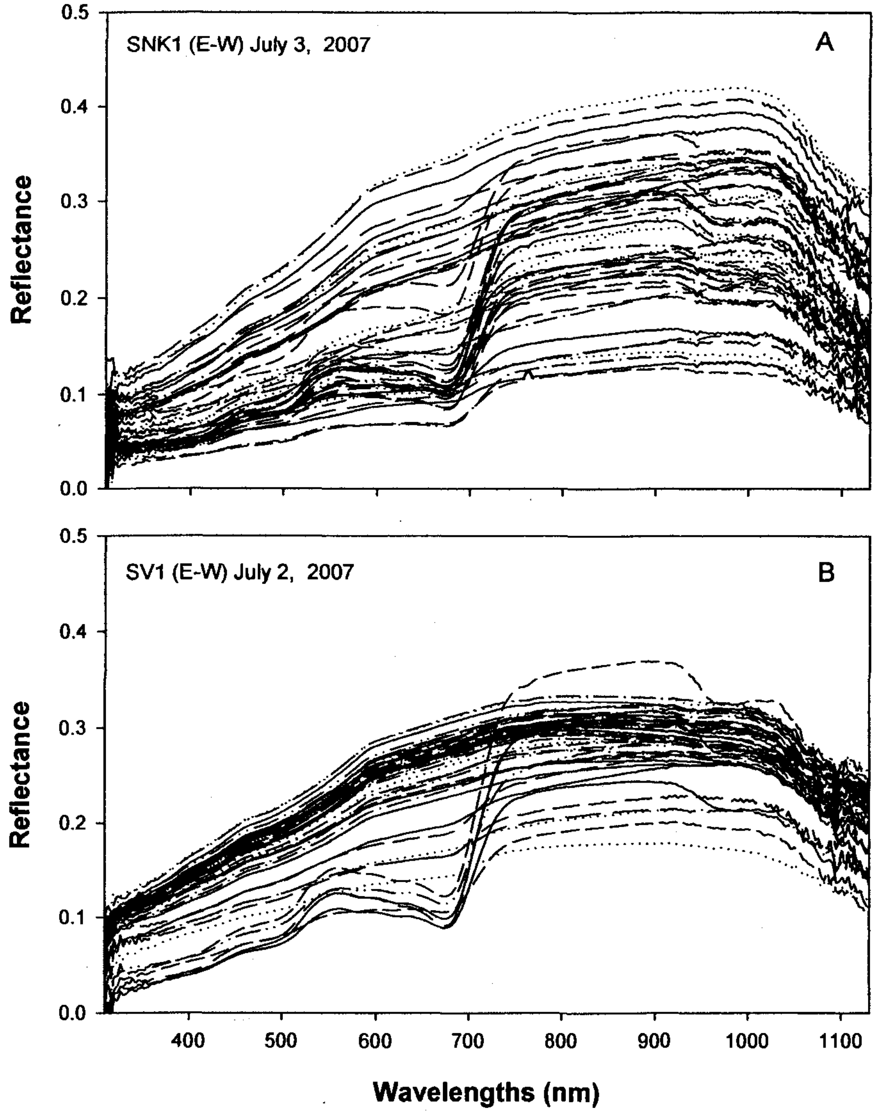

Figure 3-1. Reflectance spectra taken along a 50 m transect in the east-west direction at Snake Valley 1 site (A) and at Spring Valley 1 site (B). Spectra are representative of various ground surface constituents and were taken on July 2, 2007 (SV1) and on July 3, 2007 (SNK1).

A larger number of high NDVI values occurred at the SNK1 site compared to the SV1 site during early July, illustrating the effect of dense vegetation cover (~ 63%), (Figure 3-2A) versus sparse vegetation cover (~ 17.5%), (Figure 3-2B) on the NDVI values. At the SV1 site, most of the NDVI values were extremely low (<0.08), associated with >80% bare soil surfaces and low and heterogeneous vegetation coverage. The few NDVI peaks (between 0.4 and 0.64; Figure 3-2B) were mainly associated with single dense greasewood canopies with no bare soil or dead branches, whereas intermediate NDVI values (between 0.14 and 0.24) were associated with open canopies of various shrubs. Transects taken across both directions (north-south and east-west) at the SNK1 site showed a great deal of homogeneity, especially in early July when green canopy cover was high (visual observation), confirming the uniformity of species composition and density at this site.

During the end of the growing season and by the end of September, NDVI values declined strongly (between 1.4 and 2.8 fold) at the SNK1 site, depicting the dry down period for greasewood and indicating its response to water stress associated with the depletion of surface soil water, leading to an observed loss of canopy cover (Figure 3-2C). During the same period, NDVI from the SV1 site also declined in association with various combinations of bare soil, shrubs (green or dead), shadows and litter encountered along these transects (Figure 3-2D). NDVI values associated with bare soil remained unchanged. However, NDVI soil values varied significantly between the two sites, with SNK1 having ~ 1.6 times higher values than SV1. These variations in soil red and near-infrared reflectance characteristics were also shown by the raw spectral reflectance curves (Figure 3-1) and with the ground-based NDVI time series data (not shown).

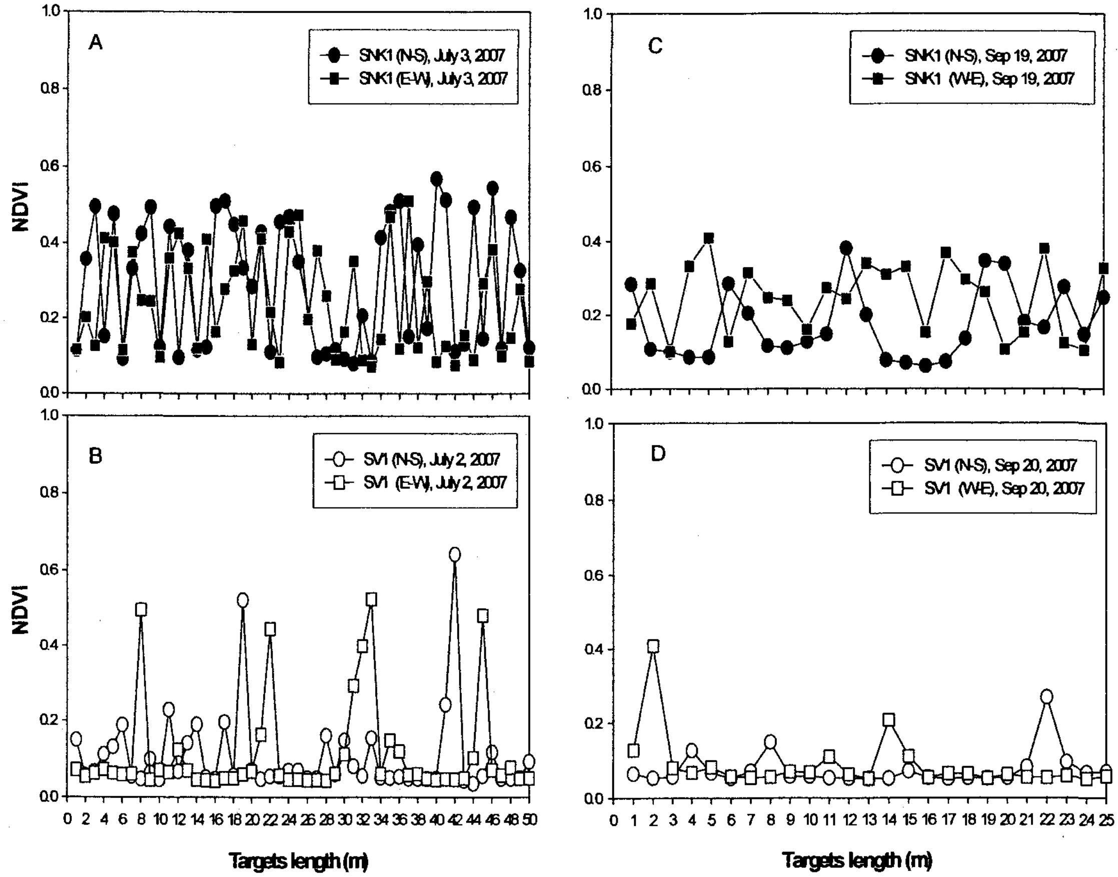

Figure 3-2. Comparison of transect NDVI between the Snake Valley 1 site (A-C) and the Spring Valley 1 site (B-D).
Transects were taken along a 50 m distance in the north-south and east-west direction on July 2, 2007 (SV1) and on July 3, 2007 (SNK1). Transects were also taken along a 25 m distance in the north-south and west-east direction on September 19, 2007 (SNK1) and on September 20, 2007 (SV1). All transect spectra were resampled to Landsat-5 TM red and near-infrared spectral bands prior to NDVI calculation.

Comparison of ground-based NDVI, transect NDVI and Landsat NDVI

Transect and satellite NDVI values deviated from the 1:1 line. However, a significant degree of correlation did exist ($r = 0.79$, $P < 0.001$), (Figure 3-3A). In all cases, transect NDVI values were between 1.4 to 2.7 fold higher than satellite NDVI values. This may partially be explained by the difference between the overall reflectance properties of the integrated plot components within a single pixel and localized ground measurements in which the nature of the measured target was relatively random and dependent on the transect interval.

NDVI values from the SKR-1800 NDVI sensors were 2 fold higher than the NDVI values obtained from transect measurements. In general, there was a good agreement between the NDVI values obtained with these two techniques ($r = 0.73$, $P < 0.001$), (Figure 3-3B). However, greater variation occurred with sagebrush NDVI measurements. Based on field observations, sagebrush canopies varied widely in canopy density, resulting in larger error bars. Greater variability in NDVI transect data at SV1 also existed for rabbitbrush and greasewood. This variation in NDVI values was supported by field observations, as not all plants within the same species and within the same location showed the exact same canopy cover, greenness, size or age. It should be noted, that during the September transect run (25 m), only two greasewood shrubs were encountered along the west-east direction and only one along the north-south direction at the SV1 site (Figure 3-3B).

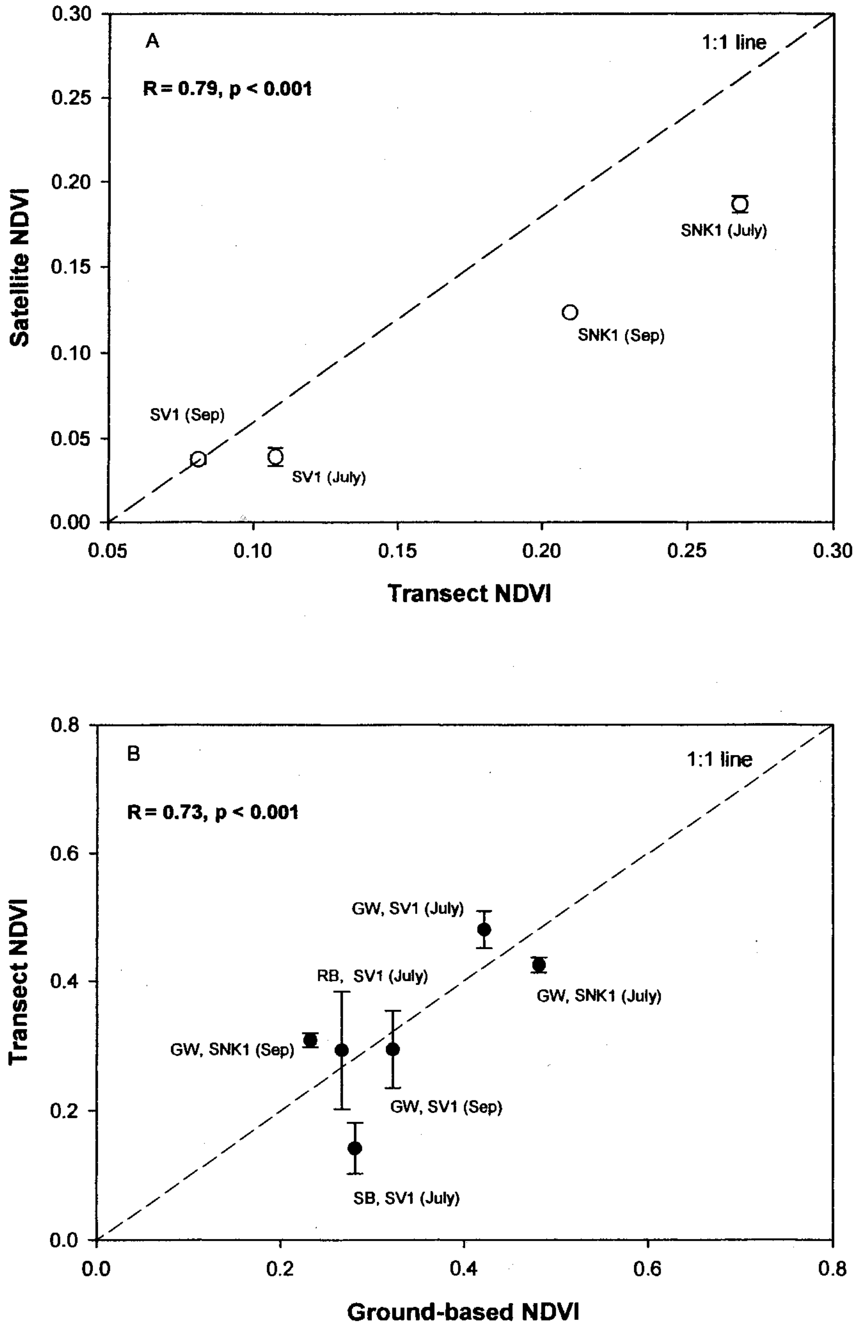

Figure 3-3. Average satellite NDVI (cloud free days) versus average transect NDVI (A) and average transect NDVI versus average ground-based NDVI (B).
Satellite NDVI data represent the plots from which the transect data were measured. Ground-based NDVI data represent time series of average midday (11:30-13:30h) NDVI values from individual shrubs: greasewood (GW), sagebrush (SB), rabbitbrush (RB) all measured with the SKR-1800 radiometer at the Spring Valley 1 site (SV1) and the Snake Valley 1 site (SNK1) in July and September. Error bars represent standard errors of the means. Dashed line represents 100% agreement.

Correlation between ET, R_n, NDVI and ET estimation

ET values were consistently higher at the SNK1 site than at the SV1 site due to the distinct contrast in vegetation cover (dense versus sparse) between the two sites (Figure 3-4). The cumulative total ET estimates for the period between May 5 and September 30, 2007 was 11.0 cm for the SV1 site and 34.9 cm for the SNK1 site. Thus, a 3.6 fold increase in vegetative cover was associated with a 3.2 fold increase in ET. The ET curve from the SNK1 site also revealed a distinct contrast between high ET values associated with green full canopy cover during the late-spring and early-summer periods and lower ET values associated with the dry-down period during late-summer. This dynamic trend in ET was similar to the trend observed in the greasewood NDVI time series measured with the SKR-1800 radiometer (see previous chapter). However, ET values remained stable over time, indicating limited soil evaporation and plant transpiration activity associated with the sandy soil and the sparse and heterogeneous vegetative cover. For the same period, R_n values were approximately 23% higher at the SNK1 site (higher vegetative cover, darker soil) compared to the SV1 site. At both sites, R_n was higher during the early spring and summer periods, but gradually decreased following the shift in season (September-early fall).

Cloud free Landsat derived NDVI values were correlated with daily actual ET values for the growing season (May to September) for both experimental sites. NDVI values included all Landsat overpasses between May and September, except for August 3 data and September 4 data, which were discarded because of cloud cover. When correlations were established for each individual site, the correlation coefficients were low ($r = 0.55$ for SNK1 vs. $r = 0.45$ for SV1) due to the small dataset of each site.

However, when data were combined across the two sites, the linear correlation became stronger ($r = 0.88$, $P < 0.001$), (Figure 3-5).

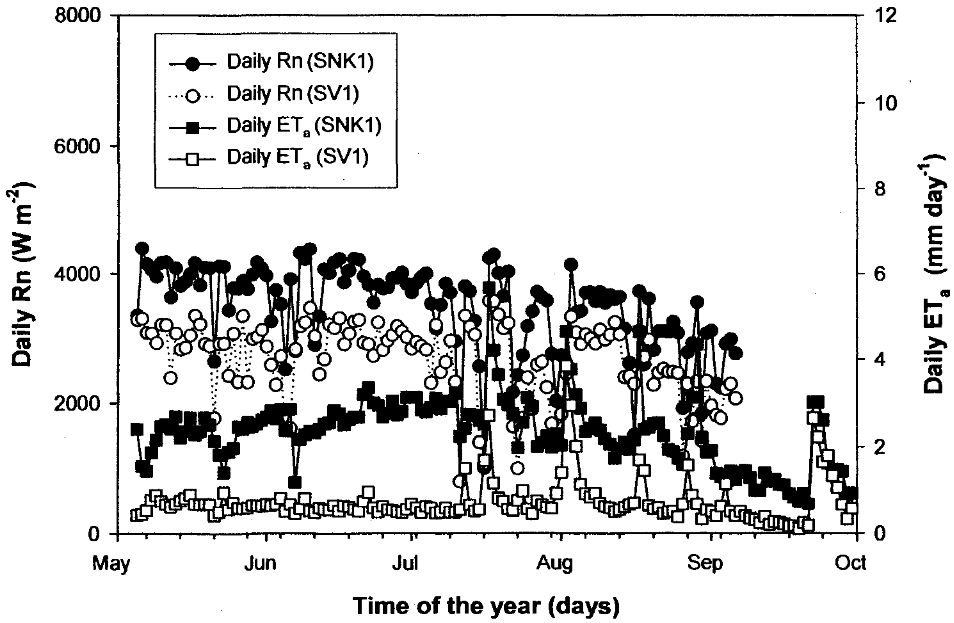

Figure 3-4. Average daily net solar radiation and average daily ET$_a$.
Data were acquired over the experimental period between May 5 and September 30, 2007. Average net solar radiation values are from Snake Valley 1 site (closed circles) and from the Spring Valley 1 site (open circles). Average daily ET$_a$ values are from Snake Valley 1 site (closed squares) and from the Spring Valley 1 site (open squares).

This correlation was obtained based on data from the center pixel where the eddy flux tower was installed. When correlations were developed based on the averaged values from 25 pixels (25 m × 25 m each) surrounding the tower ($r = 0.89$, $P < 0.001$), or 25 pixels south of the tower ($r = 0.88$, $P < 0.001$), the r values were relatively similar to the center pixel. This lack of improved correlations with increased pixel numbers was most likely related to the non significant difference in percent vegetation cover between the various plots at each site, as indicated by the percent cover data estimates (Table 3).

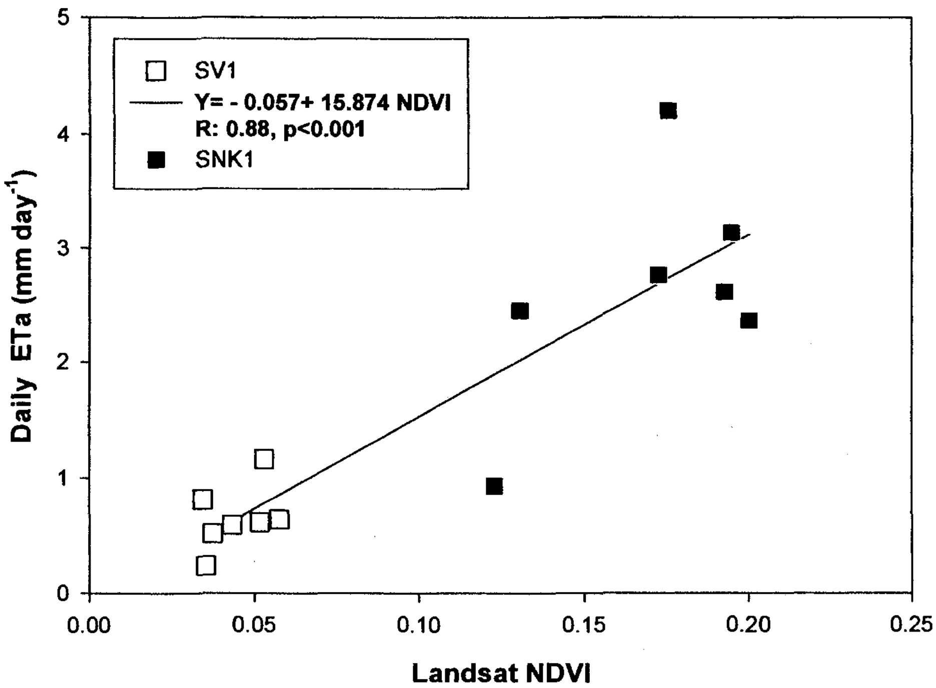

Figure 3-5. Actual evapotranspiration (ET_a) as a function of Landsat NDVI. Data represent measurements acquired during the experimental period between May and September, 2007 over Snake Valley 1 site (closed squares) and Spring Valley 1 site (open squares). Linear regression equation and *r* are shown.

Correlations were tested between ET, satellite NDVI, PAR, T_a and R_n to determine if the ET-NDVI relationship could be enhanced. R_n produced the highest prediction with ET ($r^2 = 0.82$, $P < 0.001$) and with NDVI ($r^2 = 0.78$, $P < 0.001$), while PAR produced the poorest prediction ($r^2 = 0.35$, $P < 0.001$). All possible multiple linear correlations were tested with every variable to determine if autocorrelation and multicollinearity problems existed. R_n was also correlated with PAR, but because of problems of multicollinearity, PAR was eliminated from the NDVI prediction equation. The final and improved ET predictive equation ($r^2 = 0.86$, $P < 0.001$) was based on introducing R_n and including NDVI in the exponential term of the regression equation:

$$ET = -3.670 + 0.00137\, R_n\, e^{NDVI} \qquad (6)$$

Weighting ground-based NDVI

Weighted ground-based NDVI values calculated from the application of equation (4) for the SV1 site and equation (5) for the SNK1 site were highly correlated with all cloud free Landsat NDVI values from May through September across the two sites (r = 0.97, $P < 0.001$), (Figure 3-6). Correlated NDVI values from the SV1 site were 3 to 5 times lower than NDVI values from the SNK1 site. This difference was due to the difference in vegetation cover between the two sites. High deviations from the 1:1 line were associated with weighted NDVI values > 0.20 from the SNK1 site. These values were associated with peak ground-based greasewood NDVI values > 0.50 recorded on May 15, May 31, June 16 and July 18 of 2007, explaining the curvilinear shape of the regression curve which originated from the actual weighting of these high ground-based NDVI values. In this context, a value of approximately 0.20 may represent a threshold level for weighted ground-based NDVI values, as satellite NDVI values no longer exhibited a good correlation with the weighted NDVI values.

Comparing the two NDVI values per overpass indicated that weighted NDVI values were as much as twofold higher than Landsat NDVI values at the beginning of the growing season. A high degree of overestimation occurred at the beginning of the growing season associated with ground-based greasewood NDVI values > 0.5 at the

SNK1 site and greasewood, sagebrush and rabbitbrush values >0.37 at the SV1 site. Underestimation occurred toward the end of the growing season associated with ground-based NDVI values for all shrubs which had <0.30 at both sites. The best coefficients of determination were obtained in the middle of the growing season with almost a 100% agreement on July 2 at the SNK1 site and on July 18 at the SV1 site. One of the possible reasons for this bias that occurred in the early and late periods of the growing season, especially at the SNK1 site, was the fact that the single monitored greasewood plant differed slightly in its response during overall green-up and dry-down periods compared to the other greasewood plants at this site. This explanation was supported by field observations throughout the experimental period.

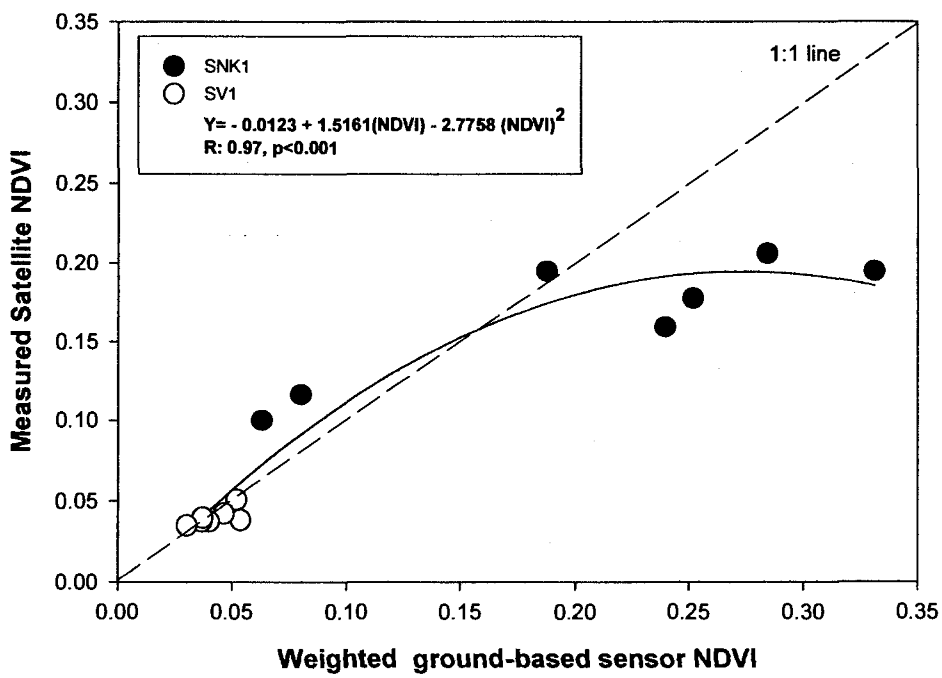

Figure 3-6. Correlation equation for weighted sensor NDVI vs. satellite NDVI for Spring Valley 1 site and Snake Valley 1 site.

Discussion

Improved evapotranspiration estimation using remotely sensed techniques and ground measurements is essential for future groundwater management and planning in semi-arid environments. Recently, much effort has been directed towards the development of remotely-based multi-scale measurements, such as repetitive spectral reflectance sampling in the field for validation or comparative purposes (Cheng *et al.*, 2006; Claudio *et al.*, 2006; Gamon *et al.*, 2006a; McCabe & Wood, 2006). In this study, a combination of continuous NDVI and transect field sampling; percent cover estimates and meteorological and satellite measurements in sparse and dense vegetation settings were introduced. A simplified approach to scale continuous ground-based NDVI measurements acquired within the footprint of eddy flux towers, for the purpose of improving satellite data interpretation and ET estimation was also presented.

The two sites were compared by identifying individual shrubs and quantifying the variation in plant density, species composition and the portion of bare soil coverage at each site. Obtaining this type of detailed field information about ground surface constituents was critical in the interpretation of ground-based field spectra and satellite based-NDVI images, as the spectral reflectance response in the red and near-infrared is complicated by the woody and leafy components of most shrubs and their open canopies (Frank & Tweddale, 2006) which often leads to misinterpretation of the final composite reflectance indices within a satellite pixel. Thus, it is essential to conduct field studies to obtain accurate information on vegetation cover and species distribution for further assessment of their contribution to the overall NDVI estimates obtained at the scale of the satellite pixel.

Transect measurements conducted during the early and late phases of the growing season provided valuable information with regard to the spectral properties of shrub species and soil types differentiating the two sites. Spectral reflectance sampling along a 50 m (July) and 25 m (September) transect provided clear spatial differentiation between the SV1 site and the SNK1 site in terms of vegetation cover. These spatial differences were featured in the spectral reflectance and NDVI responses indicating the frequent presence of bare soil surfaces and backgrounds at the sparse vegetation SV1 site and the presence of dense vegetation cover at the SNK1 site. Furthermore, comparison between transect NDVI measurements across time within the same site and between sites revealed very distinct patterns of green vegetation with regard to their seasonal development and their response to the availability of water. This dynamic nature of NDVI over time and across space was previously noted by Gamon *et al* (2006a) in a chaparral ecosystem using a mobile tram sampling system. Additional information on other land surface constituents such as shrub shadows, dead branches, stems, underlying litter and soil backgrounds was also captured in various combinations with vegetation along the transects, providing more ground information to relate to the 25 m by 25 m Landsat pixel scale.

NDVI time series generated from the daily ground-based NDVI measurements using the SKR-1800 sensors allowed for a more detailed distinction between the two classes of soil types and between the different plant species based on tracking their phenological behavior (NDVI assessment supported with visual observations) throughout the entire growing season. Detailed information regarding NDVI time series data was provided in the companion study (chapter 2). In this study only NDVI data that coincided with Landsat overpasses was utilized in the analysis.

Using repeated field spectral reflectance measurements at a finer scale allowed for the retrieval of key information on various field components and processes that are impossible to capture or discern by the coarse resolution of most satellite platforms, including Landsat. Therefore, this ground-truth data can be used to validate remotely sensed information extracted from coarser spatial and temporal resolution platforms. This view on the importance of repetitive field spectral reflectance sampling was also shared by Cheng *et al* (2006) and Claudio *et al* (2006) in recent Spectral Network (SpecNet) group studies.

Comparison between transect NDVI data and Landsat NDVI corresponding to the same plots where transect measurements were taken in July and in September, 2007 resulted in an r of 0.79. In virtually all cases, transect NDVI values were higher than the pixel NDVI. There are many possible reasons for this discrepancy, such as the randomness of the measured surfaces in the field dictated by the transect interval and distance. The number of shrubs encountered within each transect line may not have been proportional to the relative distribution of the various shrubs (SV1) or the dominant species (SV1, SNK1) within each plot. Here, we used a simplified transect measurement approach that did not account for factors controlling species distribution within each site. Plus, the spatial resolution of the satellite plays an important role in determining the overall spectral contribution of soil versus shrubs when comparing the integrated plot components within a single pixel to localized ground measurements. In this case, for the entire Landsat 25 m by 25 m pixel size, the fraction of bare soil dominated the fraction of shrubs at the SV1 site. This domination, supported by percent cover measurements, intensified even further towards the end of the growing season. Additionally, minor inconsistencies associated with the inherent nature of field measurements may have also played a role in degrading the correlation between ground and satellite measurements. For example, the ability to obtain field transect measurements consistent with Landsat overpass days was not possible for both sites at the same time, as transect measurements in July and September were off by one day for the SNK1 site. Despite these problems, using transect data provided valuable information with regard to interpreting Landsat imagery from the aggregation of field measurements and observations, particularly over the two different sites and time periods.

Further improvement of field spectral reflectance sampling approach used in this study is recommended for future research in order to improve the degree of correlation with satellite data. One might opt for developing a more refined transect sampling approach that accounts for the variability in bare soil fraction, species composition, size, and distribution to be more representative of the satellite spatial resolution. This can be done by collecting geographic coordinate data in the field for various constituents to accurately locate them in the satellite image. A similar approach was adopted by Frank & Tweddale (2006) to determine the appropriate spatial resolution of airborne imagery to increase the accuracy of vegetation cover measurements. Incorporating percent cover measurements coincident with satellite overpass will further enhance the validity and the accuracy of the information obtained from field measurements.

Correlations between NDVI data generated from the transect measurements and the SKR-1800 data on the main shrub species representing the SV1 and SNK1 sites, revealed variations in plant response. In fact, plants from the same species and within the same location varied in their NDVI values based on their chlorophyll content (as inferred from tissue N concentrations and chlorophyll index values, reported in chapter 2) and the contribution of soil background relative to their canopy density. It should be noted that the NDVI wavebands from the transect measurements and the ground-based NDVI sensors were similar and equivalent to Landsat red and near-infrared bands. Therefore, error related to dissimilarities in wavebands between these different remote sensing sensors was not a factor. The difference in ground-based NDVI values between observed in our study was indicative of the capability of high spatial resolution field sensors (25° FOV) to detect smaller spectral variations within the same species and between different species. Thus, data from these ground-based measurements provided important information about variations in plant bio-physiological characteristics (as reported in chapter 2) supporting the findings of Goward *et al* (1994). This type of information is impossible to obtain at the Landsat scale, revealing a significant gap between satellite measurements and field measurements and stressing the importance of field spectral measurements to refine the interpretation of satellite data.

The remote sensing data collected in this study were used to not only assess the impact of soil and plant spectral response on the integrated NDVI values at the pixel level but also to develop empirical relationships with ET_a. The linear regression equation between daily ET_a measured by the eddy covariance method and Landsat NDVI yielded a strong relationship ($r = 0.88$, $P < 0.001$) when data were combined across the five month experimental period (May to September) and across the two sites (SV1 and SNK1). This correlation was higher than the one obtained by Nagler *et al* (2005a) for ET data correlated with MODIS-NDVI combined across four sites of riparian species over a four year period ($r = 0.68$, $P < 0.05$). Studies conducted by Nagler *et al* (2005a, 2005b) found that ET was more tightly correlated with the Enhanced Vegetation Index (EVI) than with NDVI for the apparent reason of saturation problems usually encountered when using NDVI. EVI has been recommended under such conditions as research suggests that it lessens the effects of soil background, atmospheric scattering and biomass saturation (Huete *et al.*, 2002). Errors associated with atmospheric correction algorithms are inherent in most remote sensing studies and they vary with each satellite platform. However, NDVI saturation effects are unlikely to occur in sparse and heterogeneous semi-arid landscapes such as in the present study. Furthermore, Huete *et al* (2002) found that NDVI had a higher range in values than EVI in semi-arid areas, which was also the case in this study (not shown). Uncertainties related to EVI and NDVI performance across various ecosystems and landscapes using multiple remote sensing platforms still need to be verified. Similar thoughts were also shared by Cheng *et al* (2006).

Incorporating meteorological variables along with remotely sensed vegetation indices was undertaken to improve ET estimations in this study. Net solar radiation (R_n) produced the highest prediction of ET ($r^2 = 0.82$, $P < 0.001$) and was used in the final predictive regression equation (eq. 6) that yielded an r^2 value of 0.86.

This coefficient of determination was higher than that reported by Nagler *et al* (2005a, $r^2 = 0.82$; 2005b, $r^2 = 0.74$) who used daily air temperature and EVI combined across tower sites, riparian species and years. The ability to estimate ET from remotely sensed data by incorporating meteorological parameters such as air temperature or solar radiation is supported in part by Nemani *et al* (2003), who indicated that meteorological variables like solar radiation and temperature along with water are the most important factors influencing plant growth and therefore surface energy fluxes such as ET. Incorporating ground-based meteorological measurements that have been identified as being key factors influencing ET estimations from satellite measurements has become a common practice in ET-remote sensing studies (Nagler *et al* 2005a, 2005b, 2007; Wang *et al.*, 2007). Given the dynamic nature of energy fluxes, ET estimates are closely related to meteorological variables, ecophysiological features of plant communities, water availability, soil type and geography. As such, the resulting ET prediction equations may be site specific and not transferable to other regions or conditions without extensive validation work and testing. Therefore, the simple regression equation proposed here may be used for estimating ET over larger heterogeneous vegetated areas in the Great Basin. However, further validation and testing is needed to quantify estimation errors and determine what type of adjustments are needed when extrapolating this approach over different valleys and community types.

The strong regression relationship ($r = 0.97$, $P < 0.001$) between satellite derived NDVI and weighted ground-based sensor NDVI for the two study sites over time, suggests that ground-based NDVI measurements on individual shrubs and bare soil surfaces can be successfully scaled across landscapes to represent satellite pixel size NDVI estimates. However, we believe that these results have to be interpreted with some caution, as the ground-based measurements were based on a single shrub per species within an area of 625 m^2. Still, the results presented here revealed some very interesting spatial and temporal features associated with NDVI measurements acquired at different scales. In this regard, direct comparison of NDVI values from individual shrubs showed a gradual decline in NDVI values from May to September, relatively consistent with the decline showed with satellite-based NDVI. However, ground-based NDVI values showed a slight increase on the July 18 overpass in response to summer rainfall pulses that occurred on July 11 and on July 16, which was not captured by Landsat NDVI. Subtle changes in phenological development following a response to climatic fluctuations throughout the season are usually common in sparsely vegetated semi-arid regions, but they are apparently not captured at the coarser spatial scale. An obvious explanation for that is the overall high contribution of bare soil and backgrounds to the integrated pixel NDVI value, which seems to cause some of the features observed at the ground level to disappear at the pixel scale. Although ground-based NDVI red and near-infrared bands were compatible with Landsat red and near-infrared bands, errors associated with georeferencing and atmospheric correction methods may have also affected the correlations between weighted and satellite NDVI.

The problems of overestimation and underestimation of satellite NDVI which occurred during the early and late phases of the growing season might be related in part to the adjustment made to the percent vegetation cover data over time based on the assumption that percent cover measurements follow the same linear trajectory as NDVI. If percent cover assessments had been obtained prior to May 15 and throughout the growing season, instead of the one time measurements, it may have been possible to show that this was not the case as NDVI variations are often tightly related to greenness rather than to simple variations in canopy cover (Goward *et al*, 1994; Glenn *et al.*, 2007).

Discrepancies between weighted ground-based NDVI and measured Landsat NDVI values were more pronounced at the SNK1 site, than at the SV1 site especially during the early phases of the growing season. In the companion study (chapter 2), greasewood NDVI time series data from the SNK1 site showed that the timing of spring green-up occurred two weeks earlier than that of the same species at the SV1 site. The exact reason for this shift is not fully understood. Nevertheless, this phenomenon was not consistent for all greasewood plants at the SNK1 site, and not all plants had peak NDVI values reaching an average value of 0.67 on May 15. If this was the case, the satellite NDVI pixel value should have been higher early in May, as the SNK1 site had a uniform, dense and homogeneous stand of greasewood. Consequently, in future studies a more refined field approach is needed to account for within-species variability and reduce estimation errors by increasing the number of NDVI monitored plants based on their spatial distribution. Furthermore, instead of just using individual plants and bare soil surfaces to weight NDVI, other field background components should also be monitored and integrated into the overall signal to provide a more complete representation of what is captured by the satellite.

Overall, and despite the limitations and the possible errors that may be associated with this approach, it seems that better agreement between measured and predicted satellite NDVI values is more likely to occur during full and stable canopy development when conditions are more homogeneous over the sites. To our knowledge, this is the first documented attempt at using intensive daily timescale ground-based NDVI monitoring to scale directly to pixel level NDVI values.

Results from this study demonstrated the value of using continuous ground-based reflectance measurements as a validation and field verification tool for satellite-based products. The unique combination of meteorological measurements, satellite-derived

NDVI, ground-based NDVI measurements and intensive field observations enabled us to generate a good estimation equation for ET and a successful simplified scaling approach of ground-based NDVI. However, the preliminary approach taken in this study still needs to be verified and improved by incorporating and testing other input variables and accounting for estimation errors to overcome some of the uncertainties encountered. These results were based on one growing period and two experimental sites. Therefore, it is important to test the level of performance of this approach over larger areas and over longer time periods. Ground validation studies of this type should be pursued and improved as satellite-derived vegetation indices remains the only means currently available to estimate and study ecosystem fluxes at a regional and global scale. Thus, proper and accurate validation of satellite data from ground measurements is required to improve ET estimations especially over heterogeneous landscapes at a basin level.

Acknowledgments

We would like to thank the entire field and lab team in Dr Devitt`s lab at the University of Nevada Las Vegas for their immense assistance with field work, data entry and lab analyses. We would also like to thank Brian Bird for his help with data acquisition. Study grant funding was provided by the Southern Nevada Water Authority (SNWA) as part of the Great Basin evapotranspiration study.

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CHAPTER 4

GENERAL CONCLUSIONS

The results from this study can be summarized as follows:

1. NDVI values were higher at the Snake Valley 1 site and lower at the Spring Valley 1 site. These differences were consistent with total percent vegetation cover 17.5% for SV1 and 63% for SNK1) and ET values (11 cm for SV1 and 34.9 cm for SNK1).

2. Continuous NDVI values obtained from ground-based SKR-1800 radiometer showed a difference between greasewood from both sites. However the satellite data showed differences based on the difference in species composition and percent cover between the two sites.

3. Ground-based NDVI showed an increasing pattern during the active growing period (May to June) and a decreasing pattern at the end of the summer (July to September) providing information about the growing period of each species and information about water stress on all monitored species at the end of the growing season.

4. NDVI collected on a daily basis provided discrimination of phenological characteristics of different vegetation types throughout an entire growing season and was able to track small and subtle changes in vegetation development not possible with Landsat imagery.

5. NDVI values derived from ground-based sensors were strongly correlated with plant measurements associated with green canopy cover and water content (*r* between 0.32 and 0.98)

6. The NDVI data set allowed for detailed comparison of the two contrasting soil types that differentiated the sites, which was an important factor influencing the growing patterns of vegetation at the sites.

7. Although a good correlation existed between NDVI and ET over the entire growing period ($r = 0.88$), incorporating R_n enhanced ET prediction ($r^2 = 0.86$).

8. NDVI values obtained from ground-based sensors can be scaled from single canopies and bare soil surfaces to an integrated satellite pixel NDVI basis within the footprint of the eddy flux towers using ground measurements as weighting factors ($r = 0.97$).

Results from this study demonstrated the value of using continuous ground-based reflectance measurements as a validation and field verification tool for satellite-based products. However, the preliminary approach we took in this study still needs to be verified and improved by incorporating and testing other input variables and accounting for estimation errors to overcome some of the uncertainties we encountered. It is important to test the level of performance of this approach over larger areas and over longer time periods.

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