Diurnal NDVI Fluctuations in Semiarid Rangelands

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ABSTRACT

This study explored the diurnal cycle of photosynthetic activity of C3 plants growing in semiarid ecosystems using NDVI as an indicator metric. A field-based sensors was calibrated and deployed to record NDVI at 30-minute intervals throughout the 2009 and 2010 spring growing seasons. The diurnal pattern of NDVI consistently followed a trough-shaped trend of low NDVI values (low photosynthetic rate) during the periods of solar noon with significantly higher NDVI values (50% higher; $P < 0.001$) during the early morning and evening hours. Physiologically, the C3 plants typical of semiarid rangelands exhibit a survival strategy that minimizes evapotranspiration losses by reducing their photosynthetic rate during times when high ambient temperatures and high irradiance have created a sub-optimal environment. These results, viewed from the context of global climate change modeling, may have resounding effects as higher than previously estimated carbon assimilation levels resulting from increased photosynthetic activity would affect carbon sequestration estimates and proliferate necessary changes across global models. Additional data collection and analysis is being conducted to validate and further explore this topic.

KEYWORDS: NDVI, vegetation indices, primary productivity, photosynthesis

INTRODUCTION

The normalized difference vegetation index (NDVI) is arguably the most widely used simple band ratio (SBR) ever developed (Rouse et al., 1973; Tucker 1979). It, along with a host of other SBR's, uses various ratio's of reflectance from the red (approximately 650nm) and near-infrared (NIR) (approximately 850nm) portions of the electromagnetic spectrum to estimate above-ground vegetation productivity and photosynthetic activity. NDVI has been applied to nearly every biome around the world including numerous forest (Hall-Beyer 2003; Knight et al., 2006), grassland (Yang et al., 1998; Hall-Beyer 2003), desert (Richard and Poccard 1998; Dall'Olmo and Karnieli 2002) and agricultural areas (Doraiswamy et al., 2003; Knight et al., 2006). Some studies have used NDVI as the basis for comparison among ecosystem types including Huete et al. (1997) who reported limitations of NDVI and biome-specific differences in NDVI response.

Other studies have used NDVI as the basis for interannual comparisons of phenological trends (Reed et al., 1994; Ivits et al., 2009) and the investigation of global climate change effects on primary productivity in grasslands (Yang et al., 1998). Similarly, intra-annual NDVI curves have been used to understand photosynthetic activity within a growing season (Tedrow and Weber 2011) and make comparisons between ecosystems (Knight et al., 2006).

Satellite remote sensing platforms such as the Moderate Resolution Imaging Spectroradiometer (MODIS) give scientists the ability to sample the earth's surface at broad scales and frequent temporal periodicity and thereby construct relatively accurate models of phenological change. However, no individual airborne or space-borne sensor routinely acquires repeated estimates of NDVI for the same area within a single day. To do this, requires an *in situ* spectroradiometer and data logger. This study was designed to explore and characterize diurnal NDVI fluctuations within semiarid rangeland ecosystems relative to the effect these cycles may have on comparative studies and global ecosystem productivity models. In addition, the physiological mechanism responsible for observed diurnal fluctuations are described.

MATERIALS AND METHODS

Study area

Spectral data were collected at the O'Neal Ecological Reserve, an area of semiarid sagebrush-steppe rangelands in southeastern Idaho approximately 30 km southeast of Pocatello, Idaho (42° 42' 25''N 112° 13' 0'' W). The O'Neal Ecological Reserve receives < 0.38 m of precipitation annually (primarily in the winter) and is relatively flat with an elevation ranging from 1420 m - 1439 m ($\bar{x}$ = 1431 m). The dominant plant species include big sagebrush (*Artemisia tridentata* Nutt.) and various native and non-native grasses and forbs, including Indian ricegrass (*Achnatherum hymenoides* (Roem. & Schult.) Barkworth) and needle-and-thread (*Hesperostipa comata* (Trin. & Rupr.) Barkworth). Each of these plant species follow a C3 carbon fixation pathway. While variations in ground cover and bare ground exposure are typical of sagebrush-steppe ecosystems, at the landscape scale the O'Neal Ecological reserve can be considered quite similar to other regions of sagebrush-steppe found across the Intermountain west.

NDVI DATA COLLECTION

NDVI uses the reflectance of light from the red and near-infrared portions of the electromagnetic spectrum. Specifically, it is the quotient of the difference in reflectance values between the NIR and red bands over the sum of these same reflectance values. The bandwidths and band-centers of each specific sensor used to calculate NDVI varies, but in general the wavelength of red band-centers is 650 nm while the wavelength of NIR band-centers is 850 nm. Measures of NDVI are collected by numerous satellite sensors at temporal scales ranging from one (MODIS) to 16 (Landsat 5 TM) days or more.

To obtain repeated diurnal measures of NDVI one option was the use of a handheld spectroradiometer. This posed numerous logistical difficulties however, as 1) this option was manpower intensive and 2) a potential bias would have been introduced if the same area was not sampled in the same way during each visit. To avoid these problems and improve the sampling interval, two QuadPod instruments were used (Garrity et al. 2010).

Each QuadPod instrument measures upwelling radiation (radiance) and downwelling radiation (irradiance). The red band was sampled at 676 nm while the NIR band was sampled at 800 nm. While slightly different than the band-center wavelengths used by satellite-based sensors, these specific wavelengths characterize the regions of peak chlorophyll absorption by the red band and peak reflectance in the NIR band and fall well within the red and NIR bandwidths of all common multispectral sensors (Rahman et al. 2001; Huete et al. 2002; Sims et al. 2006). Prior to deployment at the O'Neal study area, each QuadPod was calibrated using a white reference panel (Gamon et al. 2006). Calibration was conducted continuously and throughout periods of varying atmospheric and cloud cover conditions from 1-August-2008 through 5-August-2008 with observations collected every five minutes (n = 1440 observations). Only those observations collected during daylight periods (0500hrs-2100hrs) were used to calculate the cross-instrument calibration factor (CICF; equation 1) (n = 225).

$$\text{CICF} = \frac{\text{irradiance}_{sky}}{\text{radiance}_{white\ panel}} \tag{1}$$

Reflectance (R) was determined for both the red and NIR bands by dividing radiance by irradiance and multiplying that result by the CICF (Garrity et al., 2010) (equation 2).

$$\text{R} = \left(\frac{\text{radiance}_{target}}{\text{irradiance}_{sky}}\right) x \text{ CICF} \tag{2}$$

NDVI was calculated following standard methodology (equation 3) (Rouse et al., 1973; Tucker 1979).

$$\text{NDVI} = \frac{\text{R}_{(800\text{ nm})} - \text{R}_{(676\text{ nm})}}{\text{R}_{(800\text{ nm})} + \text{R}_{(676\text{ nm})}} \tag{3}$$

Using a 60° field of view (FOV) the QuadPod instrument was mounted upon a rigid platform with the radiance sensor positioned to image an area approximately 2.4 m x 2.4 m. The spatial resolution of the deployed QuadPod was arranged to mimic the resolution of the multispectral sensor onboard the Quickbird satellite (2.4 m x 2.4 m). During field deployment, each platform was oriented with the radiance sensor facing a southerly direction (165°) to minimize platform shadows falling within the instrument's FOV and maximize collection of early morning data (Figure 1).

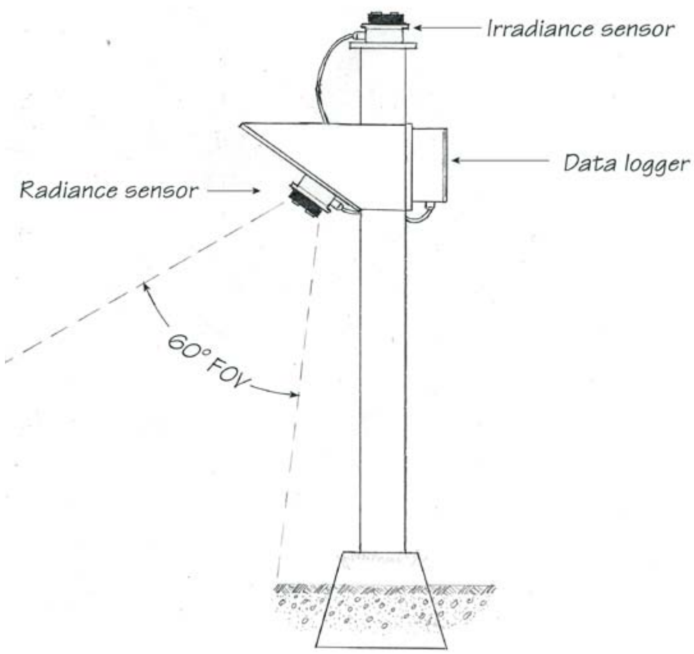

Figure 1. A drawing of the QuadPod instrument mounted upon a platform as deployed in the field.

Two QuadPod instruments were deployed on 14-April-2009 at independent locations (approximately 90 m apart) within the O'Neal Ecological Reserve and collected data throughout the remainder of April and May (a period of highly active early growth) using a sampling interval of 30 minutes. The data loggers were then retrieved and downloaded to a computer workstation. The QuadPod instruments were similarly deployed on 14-March-2010 and data loggers retrieved and downloaded later in the growing season. Reflectance for both the red and NIR bands were calculated following equation 2.

Since data collections were made throughout the day this resulted in measurements being taken across differing solar incidence angles (□). This factor plays an important part in the apparent reflectance calculation (Eq. 4). The effect of varying □ can be corrected using a bi-directional reflectance distribution function (BRDF) (Vermote et al. 1997; Collet et al 1998; Furby and Campbell 2001) and in this study, BRDF corrections for varying □ were made following Danaher et al. (2002). NDVI was then determined following equation 3 and resulting data visually analyzed for diurnal trends.

$$L_0(\lambda)=L_{sun}(\lambda)\ T(\lambda)\ R(\lambda)\ \cos(\theta) + L_{path}(\lambda) \tag{4}$$

- $L_0(\lambda)$ = observed radiance at sensor
- $L_{sun}(\lambda)$ = Solar irradiance above atmosphere
- $T(\lambda)$ = total atmospheric transmittance
- $R(\lambda)$ = surface reflectance
- θ = incidence angle
- $L_{path}(\lambda)$ = path scattered radiance

Cross-reference with satellite imagery

To aid in the interpretation of calculations made using the QuadPod instrument, four MODIS Terra (surface reflectance daily L2G [MOD09GQ] 250 m pixels) and four Landsat 5 TM (30 m pixels) scenes were acquired throughout the data collection period (April 18, 2009; May 20, 2009; April 21, 2010 and

May 23, 2010) during cloud-free or nearly cloud-free days. The MODIS Terra imagery effectively represents an overpass acquisition of 1030 hrs (mountain local time) while Landsat TM imagery represents a solar noon acquisition ($\bar{x}$ acquisition time = 1158 hrs mountain local time). These data were corrected for atmospheric effects with Idrisi Taiga (v16.03) using the ATMOSC module (Clark Labs, Worcester, MA). All atmospheric correction calculations followed the Cos(t) model (Chavez, 1996) using input parameters reported in the metadata supplied with the imagery. NDVI values were calculated for each scene and mean NDVI determined using 300 point locations randomly generated over the study area and adjacent sagebrush-steppe rangelands.

Analysis and statistical comparisons

Following retrieval of the data loggers from the field and download to a PC, all tabular data were imported into Microsoft Excel and NDVI values calculated for each 30-minute interval following equations 2-4 above. These data were then graphed for visual interpretation. To facilitate cross-reference with both MODIS and Landsat 5 TM imagery, daily NDVI values at 1030 hrs and 1200 hrs were selected and saved as new tables. In addition the daily maximum NDVI was selected and saved as a new table.

These data allowed for the comparison of NDVI values throughout each day and for a relative comparison between the *in situ* QuadPod instruments and both MODIS and Landsat NDVI values. Analysis of variance (ANOVA) was used to statistically compare maximum QuadPod NDVI values with NDVI values observed at 1030 hrs and 1200 hrs.

RESULTS AND DISCUSSION

Throughout the 2009 and 2010 spring sampling periods NDVI was measured at 30 minute intervals from 15-April through 27-May, 2009 and 1-April through 21-April, 2010. In both years, battery life was less than expected and a full spring season collection (1-April through 31-May) was not achieved. Nonetheless, a total of 46 days were sampled providing a relatively rich dataset for analysis (n = 2,208 NDVI observations).

The diurnal trend of NDVI exhibited a consistent trough-shaped pattern with NDVI values highest during the early morning and evening hours (approximately 0730hrs; Figure 2). The lowest NDVI values during photosensitive daylight hours were found within one-hour of solar noon (approximately 1230 hrs during the growing season). This paradoxical situation was consistent across both years of observation and further explored to better understand the biophysical mechanism underlying this pattern.

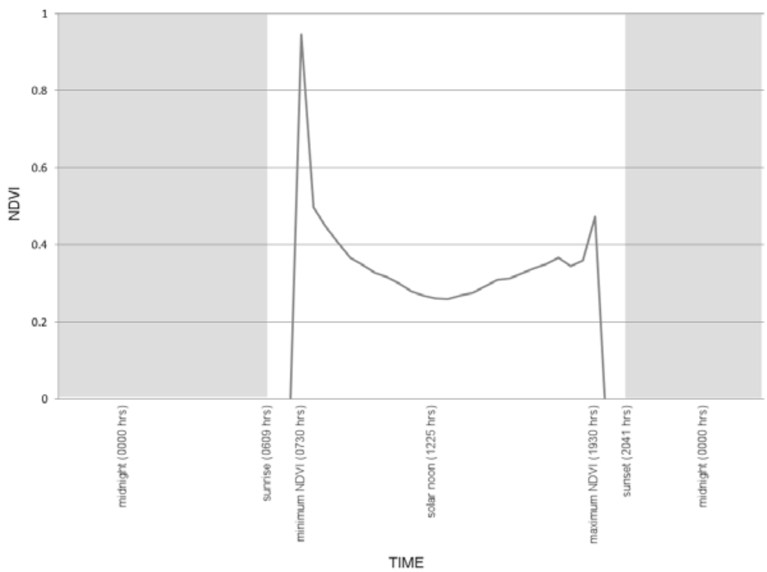

Figure 2. Example of daily NDVI pattern (May 13, 2009) typical of that observed throughout this study.

The mean difference between daily maximum NDVI ($\bar{x}$ = 0.42; SE = 0.04) and the NDVI-values recorded at 1230hrs ($\bar{x}$ = 0.17; SE = 0.02) (i.e., solar noon) was 0.25 (SE = 0.03) (Fig. 3). ANOVA comparing these values indicated significant differences ($P < 0.001$). Overall, maximum NDVI and solar noon NDVI-values followed similar curves throughout the data collection period with solar noon NDVI values up to 50% lower than maximum NDVI. The NDVI-values observed at solar noon approximate Landsat 5 TM observations suggesting NDVI for semiarid rangelands may underestimate the productivity of these ecosystems.

The mean difference between daily maximum NDVI and the NDVI-values recorded at 1030hrs ($\bar{x}$ = 0.19; SE = 0.02) was 0.23 (SE = 0.03) (Fig. 3), with ANOVA results indicating a significant difference exists between these values ($P < 0.001$). The NDVI-values observed at 1030hrs approximate MODIS Terra observations and, like Landsat TM, may underestimate the productivity of semiarid ecosystems. While NDVI-values observed at 1030hrs were slightly higher than those values observed at 1230hrs, they were not significantly different ($P = 0.44$). This trend was also observed between actual MODIS Terra ($\bar{x}$ = 0.41; SE = 0.04) and Landsat 5 TM ($\bar{x}$ = 0.27; SE = 0.06) NDVI-values, with no significant difference found ($P = 0.11$; $n = 4$). A similar trend was observed by Busetto et al. (2008) in a study comparing MODIS and Landsat NDVI imagery.

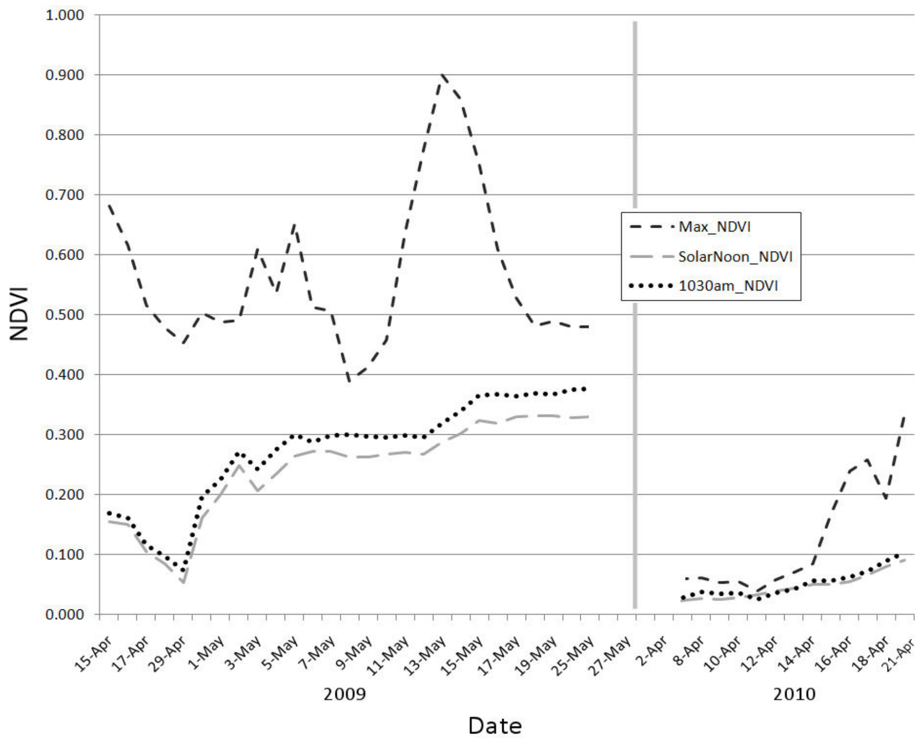

Figure 3. Daily NDVI values at 1030hrs and 1230hrs (solar noon) relative to maximum NDVI (note: lines have been smoothed using a 3-point running average).

The overall trend of NDVI was similar in both the spring of 2009 and 2010; NDVI was slightly higher at 1030hrs compared to 1230hrs and neither characterized the maximum NDVI. Between years, one should note a depressed NDVI curve early in the 2010 growing season (cf. 15-April Fig. 3) which is principally attributable to slightly cooler minimum temperatures experienced in 2010, effectively delaying the growing season (Fig. 4). In addition, spring 2010 was a slightly drier year (Fig. 5).

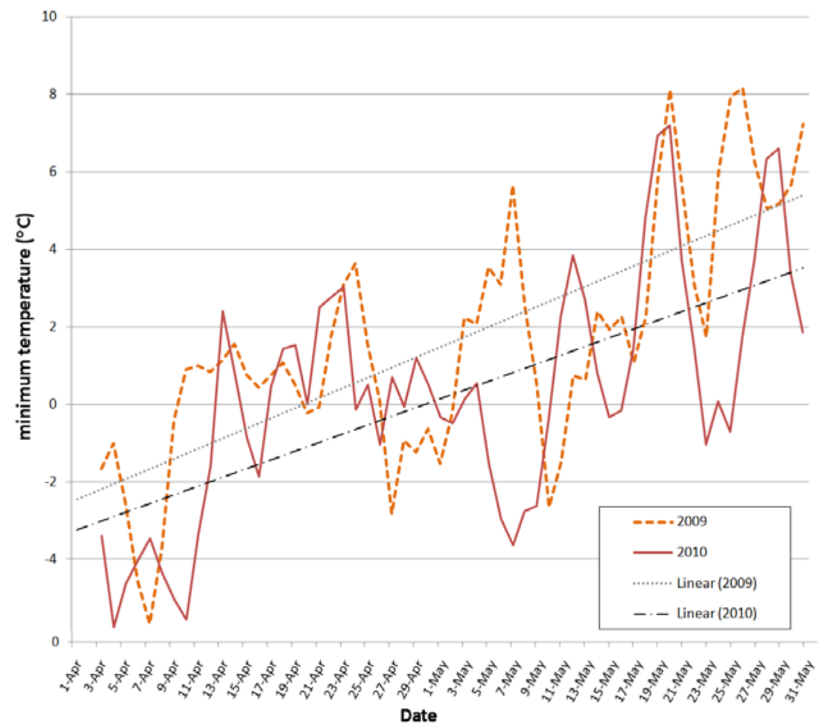

Figure 4. Minimum daily temperature throughout the spring growing seasons 2009-2010. Linear trendlines have been added to illustrate the overall cooler temperatures observed in 2010.

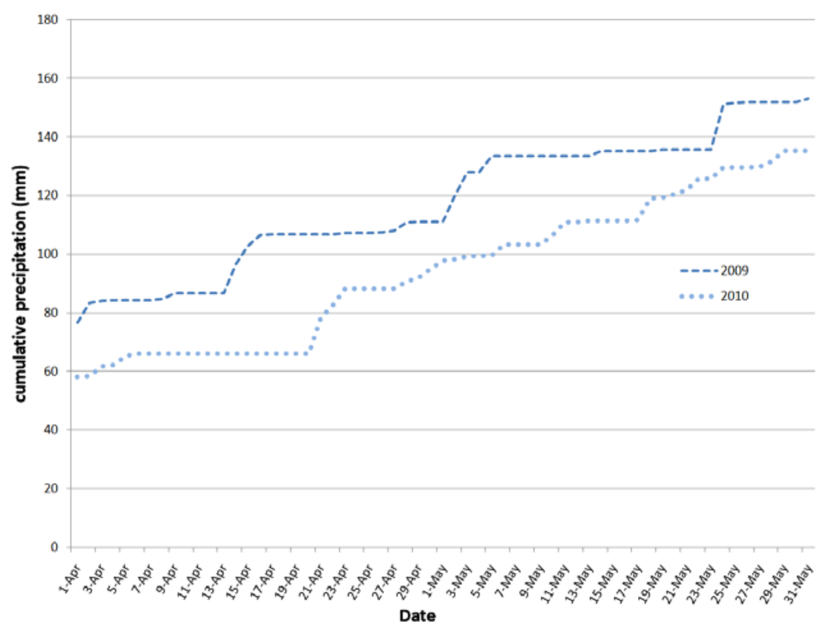

Figure 5. Cumulative precipitation throughout the spring growing seasons 2009-2010. A delayed green-up was observed in 2010 which is attributed to both cooler temperatures (cf. figure 4) and a reduction in precipitation.

Within the plant, the result of photosynthesis is the production of sugars. This process is affected by several interrelated factors, namely light irradiance, CO_2 concentration, and ambient temperature. Frederick Frost Blackman in his 1905 law of limiting factors, proposed that photosynthesis is limited by the pace of the slowest of these three factors. In this study, irradiance and temperature are of particular interest as their interaction may help explain our observations. As irradiance increases (and temperature is constant) the rate of photosynthetic activity similarly increases but ultimately reaches a plateau at high irradiance levels (cf. Blackman). When temperature increases concomitant with increasing irradiance however, the environment quickly becomes sub-optimal for the plant and light use efficiency drops rapidly (Schulze and Chapin 1987; Amthor 1989; Ryan 1991; Potter et al., 1992). These factors, combined within an arid or semiarid environment, may cause plants to close their stomata to conserve water and temporarily reduce their rate of photosynthesis (Larcher 2003). Initially, a reduced photosynthetic rate appears detrimental, however when viewed from a longer-term, ultimate perspective, this strategy allows the plant to survive in a relatively harsh environment, punctuated by diurnal periods of stress. Similar findings were reported by Hanan et al. (2005) relative to diurnal CO_2 flux in plants.

NDVI provides a metric related to the photosynthetic activity of plants (Tucker 1979; Chander and Groeneveld 2009). High NDVI values indicate plants are actively photosynthesizing while low NDVI values suggest the opposite. NDVI, and numerous other vegetation indices using the red and NIR bands, has also been used as an indicator of primary productivity. A problem arises however, in that a majority of satellite sensors use an oblique, sun-synchronous orbit and acquire imagery within an hour or two of solar noon (Barrett and Curtis 1992). This configuration is used to maximize illumination of the earth's surface and best ensure strong reflective signals are received at the sensor. Within semiarid rangelands however, this configuration may fail to capture peak daily photosynthetic activity during the growing season.

The implications of these results are many and additional data collection needs to be conducted to further explore this topic. Of primary importance is the understanding that productivity estimates based upon remotely sensed imagery(e.g., NDVI and MSAVI) appear to underestimate the productivity of semiarid rangelands, especially when NDVI values are based on satellite data acquired at or near solar noon. Acquiring satellite imagery at earlier times of the day is also problematic however as resulting imagery will be fraught with shadow and increased BRDF effects (Danaher 2002). Correcting for these effects may also be problematic as maximum NDVI is highly variable and its trendline does not exhibit the same slope as observed for solar noon NDVI. Hanan et al. (2005) reported scaling adjustments may be appropriate for light-saturated (mid-day) photosynthesis estimation but may result in an underestimate of early morning and late afternoon (light-limited conditions) CO^2 flux. These results, viewed from within the context of global climate change modeling, can have resounding effects as higher carbon assimilation levels resulting from a net increase in photosynthetic activity would affect carbon sequestration estimates within semiarid ecosystems worldwide when these estimates are derived from NDVI or similar indices.

CONCLUSIONS

Semiarid rangelands represent diverse ecosystems that are the home of numerous plant species well adapted to these harsh environments. One adaptation observed in this study is an apparent plant survival strategy where photosynthetic rate is reduced or halted in response to sub-optimal conditions that may exist during mid-day (light saturated conditions) as a result of high ambient temperatures, high irradiance, and potential net evapotranspiration losses. This study used two QuadPod instruments to measure NDVI at 30-minute intervals throughout the spring growing season. The diurnal pattern of NDVI followed a consistent trend of low NDVI values (low photosynthetic rate) during solar noon with significantly higher

NDVI values (50% higher; $P < 0.001$) during the early morning and evening hours. These results, viewed from the context of global climate change modeling, may have resounding effects as higher carbon assimilation levels resulting from a true net increase in photosynthetic activity and net ecosystem exchange would affect carbon sequestration estimates and proliferate necessary changes across numerous global models.

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