J. Range Manage.
54: A90-A105 March 2001

Mapping Weekly Rangeland Vegetation Productivity Using MODIS Algorithms

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Manuscript Accepted: April 15, 2000

Abstract

The great spatial extent of rangelands combined with recent emphasis on rangeland health has prompted a need for more efficient and cost effective management tools. The Moderate Resolution Imaging Spectroradiometer (MODIS) sensor of the Earth Observing System (EOS) will offer improved and more timely monitoring of rangeland vegetation, and, unlike any previous satellite sensor, the publicly available MODIS data stream will include estimates of rangeland productivity. These estimations of rangeland productivity can be used regionally for measuring biomass production and will be available every eight-days, with global coverage at 1-km^2 resolution. MODIS derived estimates of rangeland productivity combine remote sensing information with daily meteorological data as inputs to a mathematical model of photosynthetic conversion of solar radiation into plant carbohydrates. Vegetation productivity is a measure of rangeland vegetation vigor and growth capacity, which are important components of rangeland management and health assessment. Using MODIS data, it will be possible to characterize rangeland vegetation seasonality, estimate herbage quantity and, monitor the rates and trends of change in primary production. Consistent, objective and frequent productivity estimates will be available for even the most inaccessible rangelands.

Potential applications of weekly and annual productivity estimates are demonstrated on the Shoshone BLM Administrative District and a larger portion of the Interior Northwestern United States. Productivity estimates were derived using Advanced Very High-Resolution Radiometer data as a surrogate for the MODIS data stream. Shrub and grassland vegetation seasonality for 1991 was characterized. Herbage quantity was estimated from the 1993 shrub and grassland regional net primary production. A 5-year average productivity from 1990 – 1994 and departures from that average were calculated for the years 1991 and 1993. The measures of departure indicated that 1991 was regionally less productive and 1993 more productive than the five year average.

Collaboration between rangeland scientists and managers is necessary to realize the potential for EOS-derived vegetation productivity as a management tool. Future research will include field calibration of the productivity algorithms and exploration of new techniques for using EOS-derived productivity measures for rangeland management. Measures of rangeland productivity could become part of an integrated rangeland system analysis. This may permit differentiation between anthropogenic, biotic, and abiotic factors as the primary cause of declining productivity. Other research may include customization of biome properties for selected regions.

Key Words: Moderate Resolution Imaging Spectroradiometer, Earth Observing System, Vegetation Seasonality, Herbage Quantification, Rangeland Health

Introduction

The extensive nature of rangelands and concern for rangeland health has stimulated a need to develop data collection and analysis systems at multiple scales. Remote sensing has significant promise for development (Tueller 1989) of more reliable and economically feasible measures of vegetation production over large areas. Temporal (Muegller 1983, Smoliak 1956, Wylie et al. 1995, Kothmann et al. 1986 and Currie 1970) and spatial (Holecheck et al. 1989) variability of rangeland productivity are well documented. The Moderate Resolution Imaging Spectroradiometer (MODIS) of the Earth Observing System (EOS) has unique sensor attributes enabling it to monitor productivity dynamics at multiple scales. The MODIS will provide necessary data for input to algorithms designed for EOS by the Numerical Terradynamic Simulation Group (NTSG) at the University of Montana. These algorithms are used to derive global estimates of vegetation productivity on a weekly basis. After extensive quality control measures, this product will be available every 8 days, with 1-km^2 spatial resolution. Weekly productivity will be summed to an annual estimate of net primary productivity (NPP). Productivity estimates for rangelands will provide a practical measure for rangeland management and assessment of vegetation vigor and growth capacity. To the extent that these variables can be measured accurately, it may be possible to characterize herbage quantity, rangeland vegetation seasonality and to monitor rates and trends of primary production consistently and "instantly" over hundreds of thousands of acres. These newer methods of evaluating rangeland productivity will never entirely replace traditional methods, however, EOS weekly productivity data can be used to greatly increase timing, frequency and spatial extent of monitoring. This paper introduces the theory, algorithms and potential applications of EOS productivity products for rangeland management, with examples from the Interior Northwestern United States (Center of mass Latitude = 45°5' N, Longitude = -115°W) (Fig. 1.).

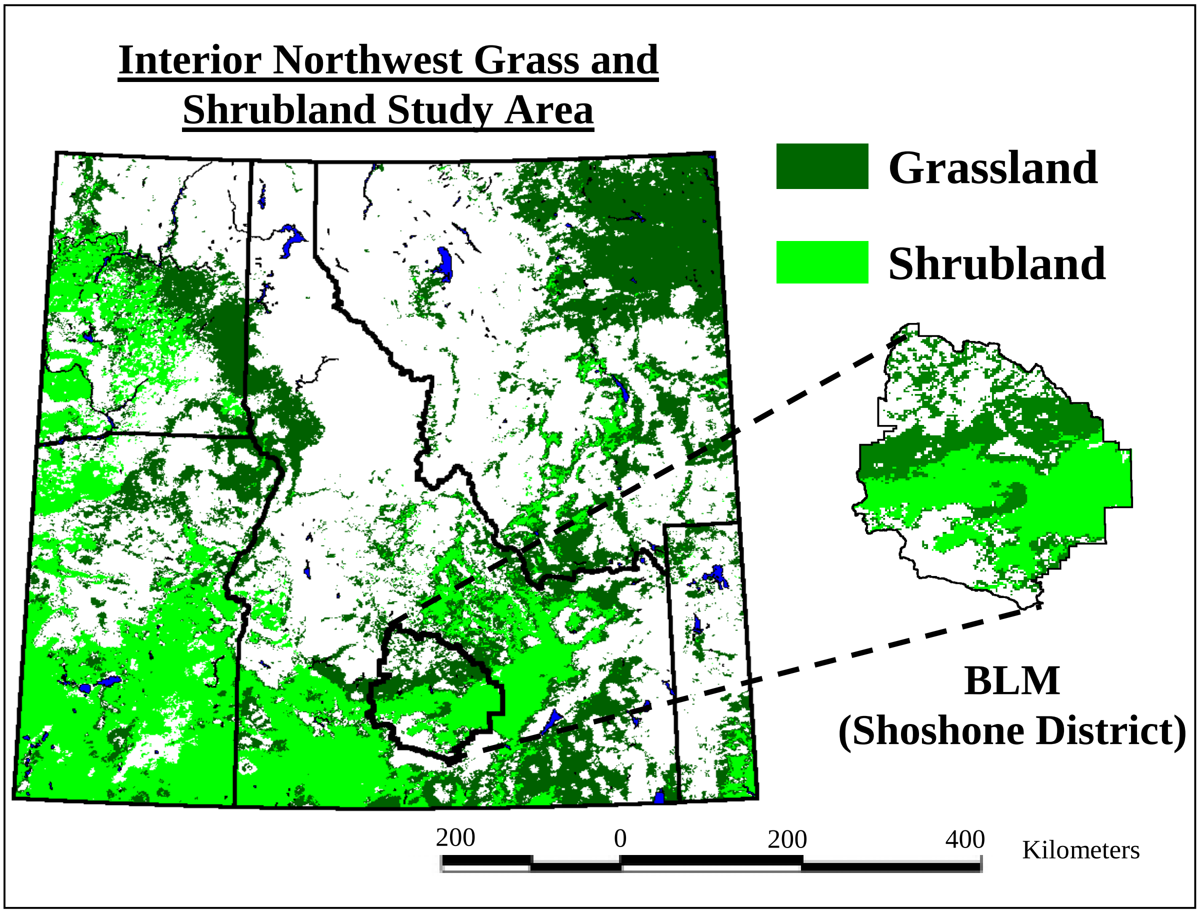

Fig.1. Interior Northwestern U.S. study area extents including the Shoshone BLM administrative district. The Interior Northwestern study region encompasses nearly 600,000 km^2 of which, grassland comprises roughly 150,000 km^2 while shrubland occupies approximately 122,000 km^2. All areas within this digital image that were not classified as “grassland” or “shrubland” were removed from the analysis. Landcover classification for the study area was extracted from the International Geosphere Biosphere Programme (IGBP) digital global landcover data (Loveland et al. 1999).

Improved Remote Sensing Capabilities

The Moderate Resolution Imaging Spectroradiometer (MODIS) was successfully deployed by NASA on 18, December 1999. Several decades of improved communications, hardware, software, data storage capacity, and satellite engineering enable the MODIS instrument to provide enhanced monitoring capabilities. A suite of satellites has been used to measure and monitor biophysical constituents of the earth’s surface, each exhibiting different characteristics. The MODIS sensor, however, is unique because it combines both spatial and spectral resolution of several satellites on a single platform. MODIS exhibits greater radiometric resolution than traditional sensors providing a broader range of measurement and therefore increased sensitivity to small changes in spectral reflectivity. The MODIS offers 36 spectral channels, as compared to 5 on the AVHRR instrument, 7 on Landsat TM or 8 on the Landsat Enhanced Thematic Mapper plus (ETM+) (Table 1). Although Landsat satellites offer

Table 1. Characteristics of the Moderate Resolution Imaging Spectroradiometer for selected MODIS wavebands.

Band	Spectral Range[1]	Spatial Resolution (meters)
1	620 - 670	250
2	841 - 876	250
3	459 - 479	500
4	545 - 565	500
5	1230 - 1250	500
6	1628 - 1652	500
7	2105 - 2155	500
8	405 - 420	1000
9	438 - 448	1000
10	483 - 493	1000
11	526 - 536	1000
12	546 - 556	1000
13	662 - 672	1000
14	673 - 683	1000
15	743 - 753	1000
16	862 - 877	1000
17	890 - 920	1000
18	931 - 941	1000
19	915 - 965	1000

[1] **Bands 20 – 36 are generally not used for vegetation reflectance.**

greater spatial resolution they exhibit a revisit time of 16 days and with clouds often yield only 2 to 3 scenes per growing season. The MODIS offers multi-spatial resolution for different applications. Calibration of the sensor is performed on-board allowing adjustments to be made while in orbit. In contrast the AVHRR has no comparable on-board calibration for visible and infrared channels. Another weakness of the AVHRR data is the lack of orbit timing control creating inconsistent overpasses and associated sun-angles. In addition, the MODIS earth location algorithm produces 8 pieces of information and uses ground control points for instrument alignment. Earth location knowledge will be accurate within 0.1 pixels at 2 standard deviations for the 1- km bands. In addition to improved sensor characteristics and temporal and spatial resolution the MODIS data stream undergoes unprecedented processing and quality assurance tests before distribution. For example, spectral radiance data are cloud filtered, atmospherically and topographically corrected using sun and look angle information to yield an accurate surface reflectance. These procedures are part of the unique MODIS data processing system (Running et al. 1994 and Justice et al.1998). This means that MODIS data will be ready to use in customized applications immediately.

Productivity Theoretical Basis

Estimation of vegetation productivity using remotely-sensed information has generally followed two approaches, (1) establish direct empirical relationships between spectral reflectance and biomass (e.g. Tucker et al. 1983 and Wylie et al. 1995) or (2) use the spectral reflectance to estimate the amount of absorbed photosynthetically active radiation (APAR) (Choudhury 1987). The first approach has proven useful for estimating live biomass. However, the second approach is likely to be more successful in predicting biomass across different climatic regimes (Choudhury 1987) and across biomes. Numerous broad scale studies (Thoma 1998, Tucker et al. 1983, Kennedy 1989 and Merril et al. 1993) have shown that live biomass is correlated to remotely sensed vegetation indices, particularly the normalized difference vegetation index (NDVI). Despite the success of regression-based predictors of biomass, they generally have limited temporal and spatial applicability. Many studies directed at biomass estimation with remote sensing derived regression-based predictors did so for one time in the growing season (Kennedy 1989, Merrill et al. 1993, Wylie et al. 1996) or focused on the end-of-season total productivity (Tucker at al. 1983), thereby limiting these models to discrete points in time. Spatial restrictions exist because regression-based equations often perform poorly when applied to conditions unlike those used to develop the relationships either due to change in scale from the place of development or a shift in site characteristics. Finally, most biomass estimation procedures involving remote sensing inputs do not explicitly include climatalogical information. In contrast the MODIS weekly productivity logic combines remote sensing data and daily climatalogical inputs with fundamental principles of plant growth. The remotely sensed data provides a snapshot of greenness and leaf area as daily weather information influences growth capacity. This approach permits the estimation of productivity across multiple range sites and biomes.

The MODIS weekly productivity model is based upon the logic of Monteith (1972 and 1977). Monteith suggested that the NPP of a well-watered and fertilized annual crop is linearly related to the amount of absorbed photosynthetically active radiation (APAR). The amount of APAR depends on the quantity of solar radiation reaching a site and the ability of the vegetation to absorb that radiation. The amount of radiation intercepted by vegetation is directly related to vegetative leaf area that can be detected using remote sensing. This makes the radiation conversion efficiency logic an attractive avenue for predicting NPP from remotely sensed inputs (Prince 1991, Prince and Goward 1995 and Hunt et al. 1994). Relying on the radiation conversion efficiency logic requires measures or estimates of global, daily photosynthetically active radiation (PAR), hence accurate estimates of NPP will depend on the quality of PAR estimates.

Monteith's formulation included a maximum radiation conversion efficiency ($_{max}$) that is attenuated by the influence of environmental factors thought to reduce growth efficiency (Running et al. 1999). Early applications of these principles assumed a universal constant for $_{max}$ across vegetation types. Later studies showed important differences in maximum efficiency between types (Russell et al. 1989). Other studies have shown that time integrals of APAR correlate well with observed NPP (Goward et al. 1985) but different relationships exist for different vegetation types, and for the same vegetation type under different growth conditions (Russell et al. 1989). It is therefore likely that plant growth and maintenance respiration costs are responsible for these differences (Hunt 1994). This suggests that APAR may be more closely related to gross primary production (GPP) than to NPP since; GPP is the photosynthetic gain before any plant respiration costs have been deducted (Running et al. 1999).

Algorithm Overview

At every 1-km^2-land pixel the instantaneous gross primary productivity is given by:

$$GPP = \quad * APAR \qquad (1)$$

where is the radiation use efficiency that is calculated from $_{max}$ * (climatic attenuation) and APAR is estimated from APAR = R_{net} * 0.45 * FPAR. R_{net} is the net incident short-wave radiation (W m^{-2} ha^{-1}) and FPAR is the fractional absorption of incident photosynthetically active radiation estimated from remote sensing. Weekly productivity (NPP_{weekly}) is given by

$$NPP_{weekly} = GPP - R_m \qquad (2)$$

where R_m is the maintenance respiration cost for fine roots and leaf mass. Currently, EOS-derived productivity estimates are calculated daily and composited to yield a weekly (8 day) product. Weekly productivity is defined as NPP + R_g (growth respiration). Annual NPP (ANPP) is obtained by summing and attenuating weekly productivity by yearly estimates of live woody tissue maintenance respiration and growth respiration costs for leaves, fine roots, and woody tissue (Running et al. 1999). Annual net primary production (ANPP) is given by

$$ANPP = \sum_{Year} Weekly - R_g - R_{mlw} \qquad (3)$$

where R_g growth respiration and R_{mlw} is live wood maintenance respiration. Although ANPP estimates do account for growth respiration (the "cost" of growth respiration is subtracted from GPP), the weekly product does not (the "cost" of growth respiration is not subtracted from GPP). Therefore, if the intended use is weekly monitoring of above ground vegetation productivity, growth respiration costs must be subtracted and allocation of photosynthate to roots must be considered.

Maintenance respiration and growth respiration are derived from relationships linking daily biomass and annual growth of plant tissues to satellite-derived estimates of leaf area index (LAI). The LAI algorithm uses the physics of radiative transfer in vegetation for six biome classes (grasses and cereal crops, shrubland, broadleaf crops, savanna, broadleaf forest and needle-leaf forest). Each biome has distinct patterns of tree and leaf architecture and patterns of spectral reflectance and transmittance (Knyazikhin et al. 1999) permitting reasonable estimates of LAI.

Considerations and Constraints

Some model constraints deserve mentioning because the EOS-derived productivity algorithm is designed to work globally using remotely sensed data at 1-km^2 resolution. First, objective parameterization of biotic variables for each biome type is difficult. For example, maximum radiation use efficiency can vary significantly across landscapes and between range sites but is held constant at the pixel (1-km^2) resolution. Similarly, other biological properties associated with growth respiration and fine root-to-leaf ratios change across range sites but are treated as a constant within a given biome. Second, as currently implemented, coarse resolution meteorological data (1°x1°) are used in the productivity algorithm. Hence, productivity estimates over areas with variable weather and climatic conditions may be subject to error. It is assumed that the remote sensing data manifests precipitation events as changes in greenness, and leaf area. The advantage of these 1°x1° meteorological data is that they are available every six hours for the entire globe. For localized applications, however, MODIS data can be used in conjunction with finer resolution meteorological data to produce productivity estimates over relatively small regions. Third, although the biological properties are biome specific (e.g. different biome characteristics for grasslands than for shrublands), they are a generic representation of that biome. For example, biome properties associated with a “grassland” or “shrubland” are the same for every “grassland” and “shrubland” pixel around the earth. To illustrate, the steppes of Mongolia are given the same parameters as short grass prairie or semi-desert grassland in North America. Error in productivity estimates could be realized using this logic, as there can be considerable variability within a given biome. Finally, although vapor pressure deficit is calculated and used to attenuate the maximum radiation use efficiency, no explicit measure of soil moisture is included in the algorithm.

Potential Applications of EOS-Derived Rangeland Productivity Estimates

Analyses of trends in NPP are useful as indicators of vegetation vigor, seasonality, and growth capacity for rangeland management and rangeland health assessment. Fortunately, remote sensing of vegetation (Reed et al. 1994) and subsequent calculation of NPP involves an implicit link to these measures of rangelands. Therefore, EOS-derived global NPP estimates could be very helpful for evaluating phenological development, herbage production, and rangeland health. Note that all demonstrative productivity examples for this paper used AVHRR imagery as surrogate information for the MODIS data stream that started in September 2000.

Monitoring Rangeland Vegetation Seasonality

Current ground-based inventory methods are not suitable for regional assessments of vegetation seasonality. Point-based sampling schemes are conducted with repeat frequencies too low to capture temporal variability and therefore provide poor representation of heterogeneous landscapes through time. Conversely, satellite-derived weekly productivity information indicates the spatial extent of vegetation response consistently and instantly over the most inaccessible rangeland. Monitoring growth and phenological development of rangeland plant communities over time permits the identification of essential growth stages. As depicted in Figure 2, temporal resolution of the EOS productivity products permit monitoring of variability in vegetation production and development. Such information may provide a beneficial planning tool to estimate turnout dates and for other grazing management decisions. Characterizing rangeland vegetation growth and development at a regional scale can help minimize susceptibility of certain species or communities to excessive defoliation during critical growth stages. Although a weekly estimate of productivity alone will not predict the emergence of specific vegetative morphological structures, it can provide an approximation of biomass accumulation across the landscape.

Vegetation behavior in moisture-limited arid ecosystems is largely driven by precipitation (Pickup et al. 1994). The sporadic and disjunct nature of precipitation on many rangelands obviates the need for high temporal resolution monitoring tools. Thus, in addition to providing insight to rangeland phenological development, weekly productivity can be used to identify areas of episodic greenup (Fig. 3.). Using satellite-derived weekly measures of productivity in response to precipitation may enable managers to customize grazing management schemes to efficiently utilize nutritious growth flushes.

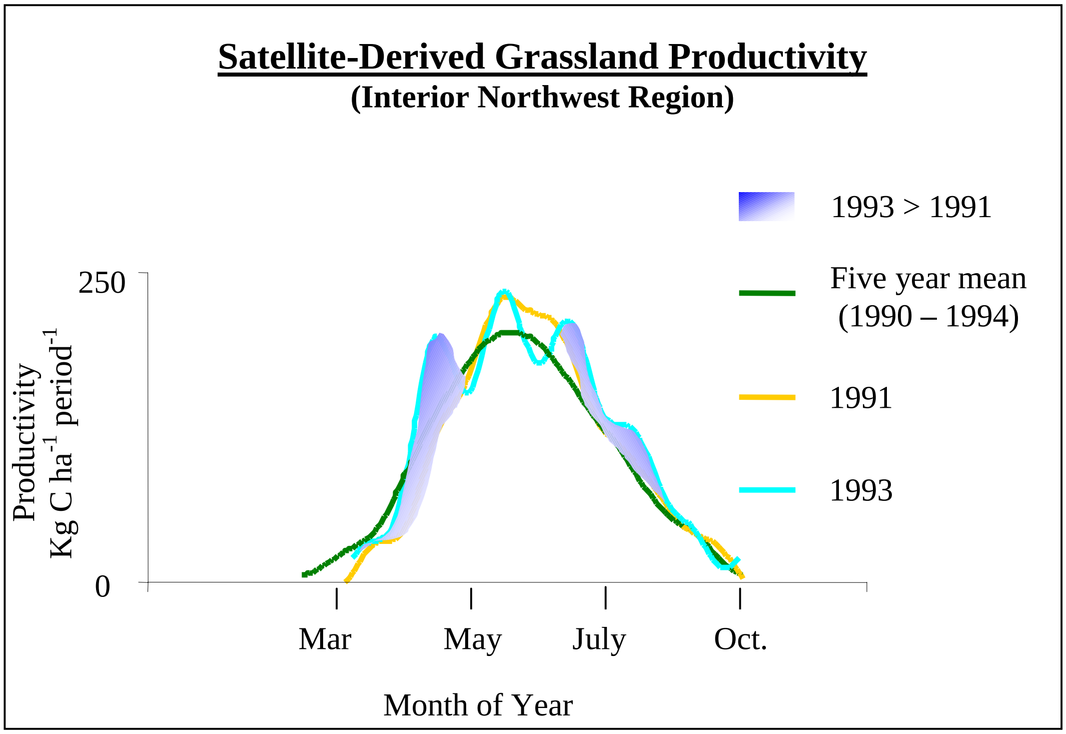

Fig.2. Comparative estimated grassland productivity (kg C ha^{-1}) derived from bi-weekly AVHRR NDVI composites for a 5-year average (1990 – 1994) and the individual years of 1991 and 1993.

Estimating and Monitoring Herbage Quantity

Primary productivity is of major ecological (Tucker et al. 1983) and economic importance. In the United States, forest and rangeland feed approximately 70 million cattle, 8 million sheep, 45 thousand wild horses and burros, 20 million deer, 400 thousand elk, 600 thousand pronghorn and smaller numbers of goats, bison, wild sheep and moose (Joyce et al. 1994). Seasonal rangeland forage conditions are highly variable both spatially (Holecheck et al. 1989, Pickup et al. 1994 and 1998) and temporally (Mueggler 1983, Smoliak 1956, Kothmann et al. 1986 and Currie 1970) potentially incurring large inter and intra-annual differences. Monitoring weekly fluctuations in productivity may enhance management decisions regarding turnout date, livestock removal, and grazing pressure modifications. Unfortunately, the proportion of photosynthate allocated to useable forage is not readily discernible in the MODIS output from that which is allocated to either unpalatable or inaccessible plant growth. Despite this precision, EOS-derived weekly productivity will provide a broad spatial estimate of growth from which herbage quantity can be inferred if vegetation composition of the local conditions is known. Another determinant in the quality of an herbage estimate is how closely the generic biome properties used by the algorithm represent site characteristics. As previously mentioned, respiration costs and photosynthate allocation to roots must be accounted for if the amount of above ground herbage is to be estimated from weekly NPP measures.

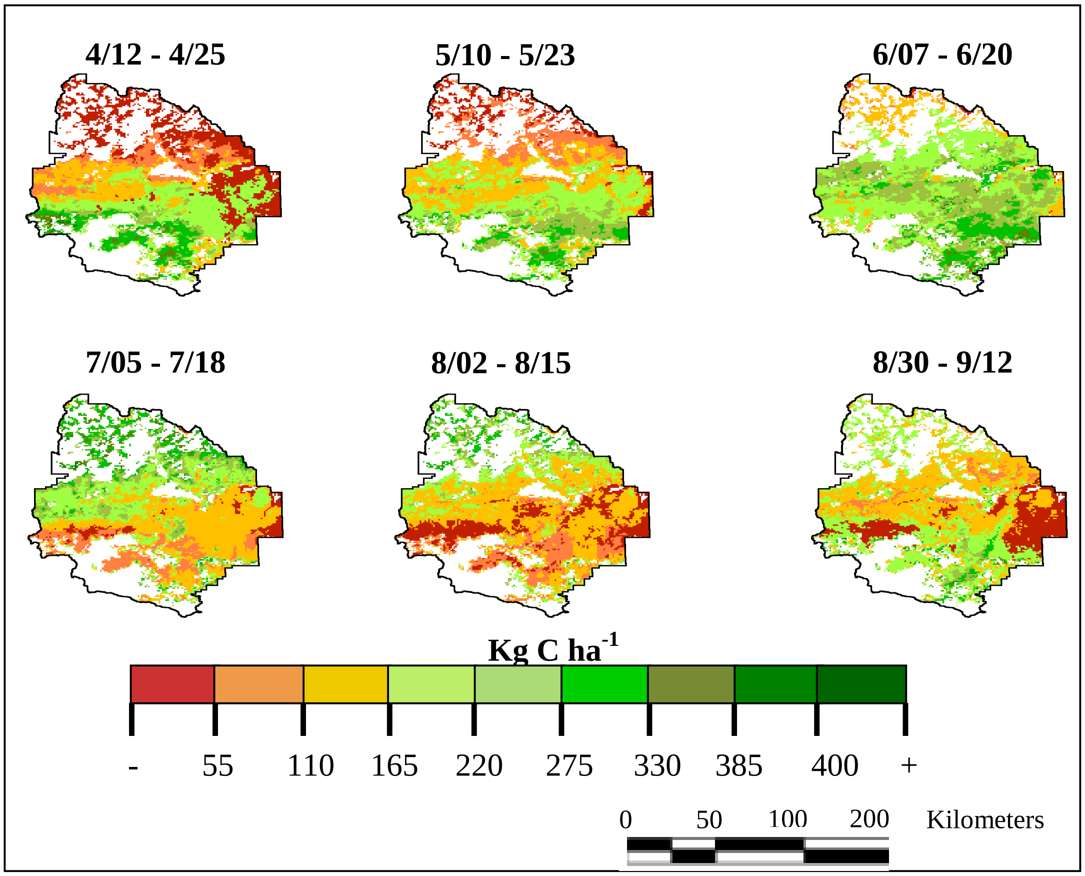

Fig. 3. Time series comparison derived from bi-weekly AVHRR NDVI composites for selected periods from 1991 of rangeland productivity for the Shoshone BLM administrative district. Dominant vegetation included in the analysis is grassland and shrubland.

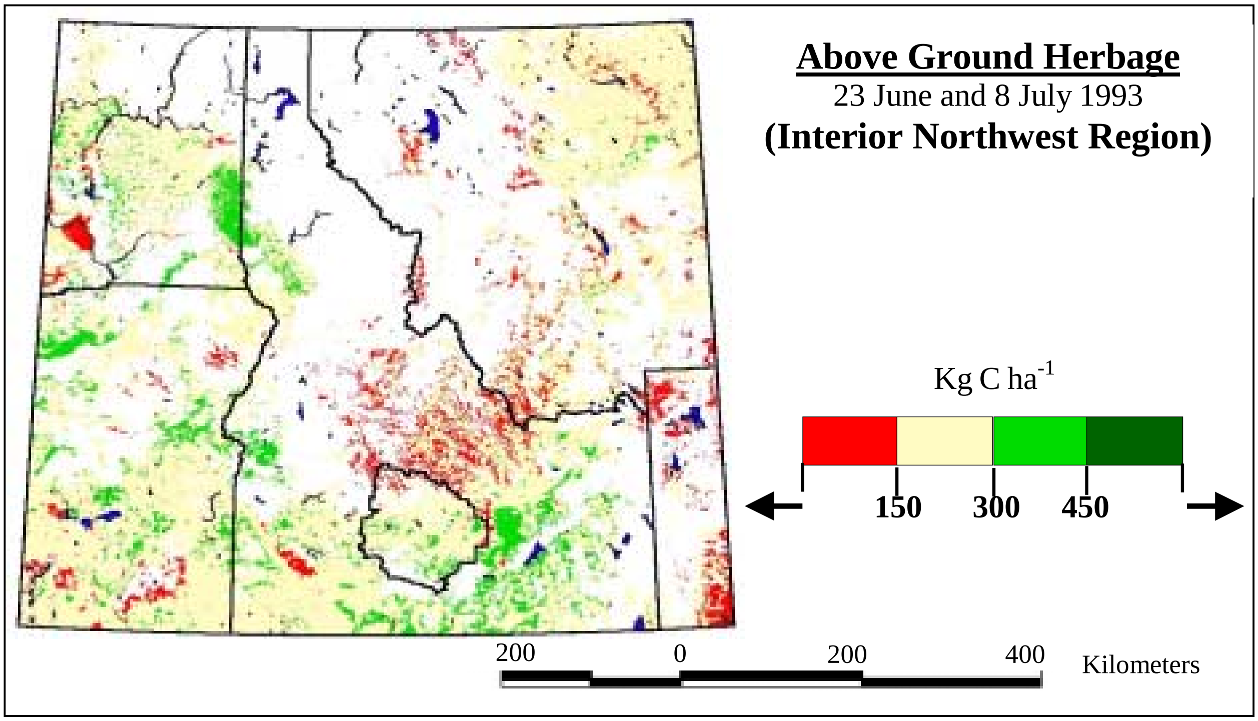

Fig. 4. Satellite-derived herbage estimate from bi-weekly AVHRR NDVI composites of the Interior Northwest for the period between 23 June and 8 July 1993. Analyses are confined to grasslands and shrublands throughout the area. Within this region grasslands and shrublands combined occupy approximately 272,000 km^2.

On non-equilibrium rangelands, it has been suggested that plant species composition does not have the assumed effect on grazing animal performance and that animal production in these areas is influenced by total grass production (Ellis and Swift 1988 and Mentis et al. 1989). Monitoring total vegetation production can be accomplished using MODIS derived productivity estimates. Herbage availability and total above ground biomass estimates are important for wildlife habitat assessment in addition to domestic livestock management (Fig. 4.).

A major obstacle in habitat assessment has been the lack of baseline habitat data. Broad-scale data collected frequently are essential for the assessment of current rangeland wildlife habitat condition. When combined with ancillary data, production estimates can facilitate habitat monitoring and determination of cumulative effects of current and past management. By modeling known parameters of a wildlife species' habitat, managers can predict the distribution or abundance of target wildlife species (Morrison et al. 1992). While weekly aboveground productivity measures may enhance momentary management decisions, its greatest utility may be as a long-term measure of rangeland condition and trend.

MODIS NPP for Rangeland Health Assessment

Despite the confusion and conflicting viewpoints surrounding rangeland health, productivity estimates may be an important component for determining whether current management practices are improving, degrading, or sustaining ecological integrity (Breckenridge et al. 1995, Busby and Cox 1994, Pickup et al. 1994). Some forms of site degradation may produce distinctive temporal and spatial patterns of change. These large-scale patterns are of particular use when assessing rangeland condition from remotely sensed data. When grazing or other management practices can be identified as a causal mechanism for change in ecosystem behavior, it is important to separate short term impacts (where the ecosystem retains the capacity for recovery) from those which reduce productivity through time (Pickup et al. 1994). While productivity estimates will not specifically identify underlying factors contributing to biomass fluctuations, they can point to areas that may be undergoing site degradation. Departure indices can be developed to aid in identifying areas that may have declining trends of productivity (Figure 5). This is particularly true if the effects of periodic precipitation can be removed from the analysis thereby focusing only on the portion of change due to an extraneous factor (management, soil instability, nutrient limitation etc.).

Productivity has been suggested as a measure of range condition and is not a universally accepted indicator of rangeland health. For example, methods of range condition assessment that focus on the climax approach are not indicative of changes in total biomass production of the range (Frost and Smith 1991). Whitford et al. (1998) found that total biomass is not a sensitive indicator of stress. Moreover, some current methods of determining rangeland condition place more reliance on change in species composition than on site productivity. Nevertheless, EOS productivity products can identify trends of decreased long-term productivity, indicating potential site degradation. The number of years required to show a decrease in productivity linked to some aspect of site degradation cannot be known without some level of uncertainty

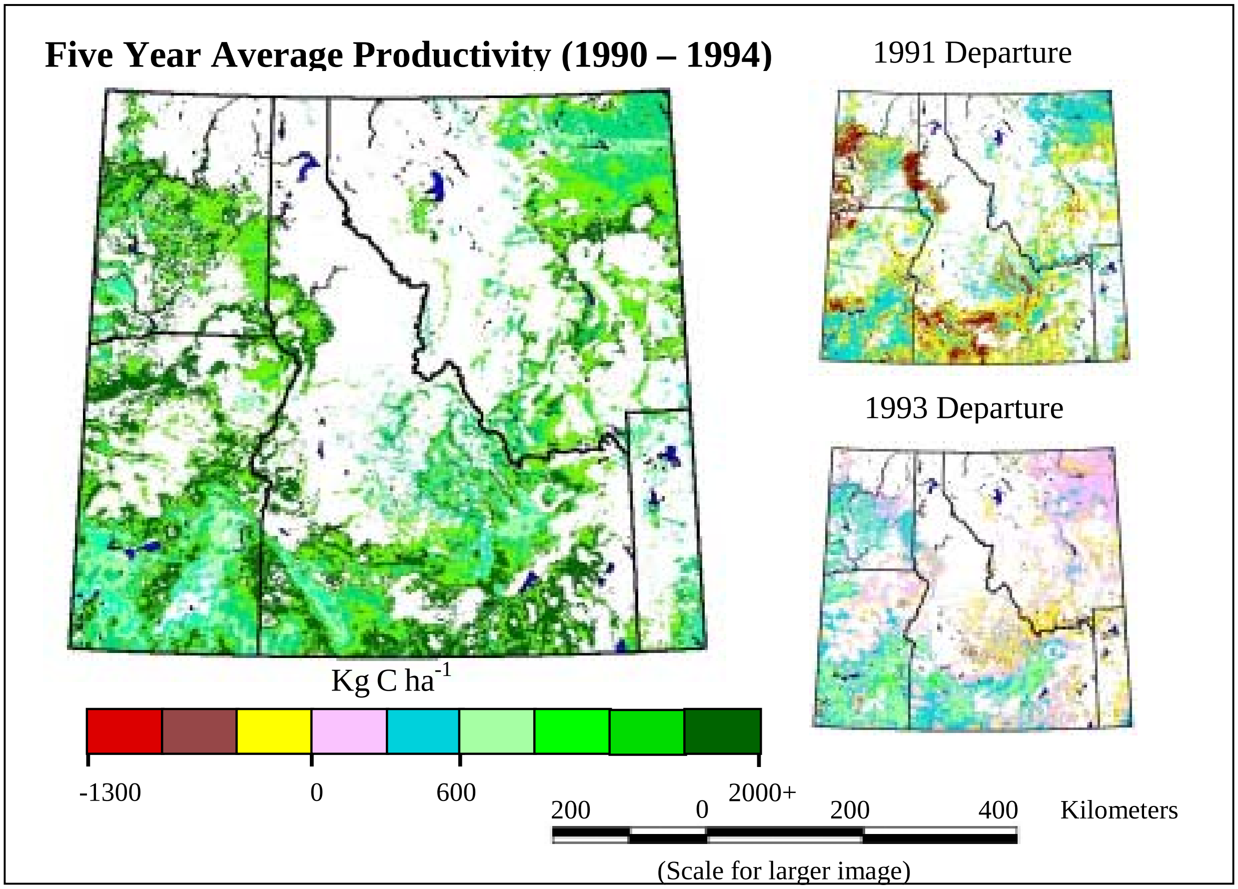

Fig. 5. Five year (1990 – 1994) mean productivity and departures from that mean derived from bi-weekly AVHRR NDVI composites for the individual years of 1991 and 1993.

and more research is needed to answer this question. Fortunately, the MODIS NPP data base will be produced and available for at least the next ten years to facilitate our understanding of rangeland productivity and management. Research directly linking site degradation to decreasing productivity is lacking, but a relationship can be inferred (Bedunah and Sosebee 1986, Thompson 1968 and Dodd and Lauenroth 1979). Thus, productivity dynamics could be a fundamental component of models or decision-making systems designed to operate with multiple sources of data simultaneously for the purpose of rangeland health evaluation.

SUMMARY

EOS-derived rangeland productivity is a high temporal resolution, objective, monitoring tool available to rangeland managers and scientists for a range, every 8 days, with 1-km^2 spatial resolution, and worldwide coverage. These data may be valuable for current and future management of rangelands since they provide insight to vegetation seasonality, herbage production, and rangeland health. Monitoring vegetation seasonality permits the identification of critical growth stages. Herbage production evaluation is both economically and biologically important. Productivity estimates allow managers to evaluate long and short-term forage availability enabling land managers to detect potential forage shortages for both domestic livestock and wildlife. In addition, monitoring biomass accumulation could provide an objective means of assessing utilization levels, thereby facilitating decisions regarding livestock removal. Finally, long-term productivity trends can be monitored with EOS-derived NPP measures providing a beneficial tool for assessing rangeland health particularly when used in tandem with other indicators of ecosystem integrity. Collaboration between scientists, managers and researchers is important to the success of these productivity estimates as a rangeland management tool. More information and productivity maps can be found on our website at http://www.forestry.umt.edu/ntsg/ or at http://modis-land.gsfc.nasa.gov/.

ACKNOWLEDGEMENTS

The authors thank and acknowledge NASA's Earth Sciences Enterprise for funding this research.

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