Special Feature: Applications of Geospatial Techniques

Comparison of Stocking Rates From Remote Sensing and Geospatial Data

E. Raymond Hunt Jr.[1] *and Brian A. Miyake*[2]

Authors are [1]*Research Physical Scientist, USDA ARS Hydrology and Remote Sensing Laboratory, Building 007, Room 104, 10300 Baltimore Ave, Beltsville, MD 20705; and* [2]*Production Manager, ValueCAD Inc, 2548 Ankeny St., Portland, OR 97214.*

Abstract

Remote sensing data from the Advanced Very High Resolution Radiometer (AVHRR) have coarse spatial resolution (1 km^2 pixel size) and high temporal resolution, which can be used to estimate net primary production regionally. The normalized difference vegetation index (NDVI) is used to determine the fraction of absorbed photosynthetically active radiation, which is sensitive to differences in growth caused by a large year-to-year variation in precipitation. The 12-year average of net primary production was used to calculate stocking rates in animal-unit months per acre for the state of Wyoming. Stocking rates were also calculated for Wyoming from 1:500 000 scale soil and climate geospatial data layers based on stocking rates from the US Department of Agriculture Natural Resources Conservation Service *Technician Guide to Range Sites and Range Condition*. In a pixel-by-pixel comparison, there was a weak but significant correlation between the 2 methods based on the spatial distribution of precipitation. There were classes of vegetation type for which the AVHRR data predicted either much lower or much higher stocking rates. More work needs to be done to reduce geospatial data uncertainties for the determination of stocking rates from both NDVI and stocking rate tables. Remote sensing indicates the actual condition of vegetation, so this is an important step in the development of regional forecasting of range condition, trend, and projected stocking rates for decision support tools.

Resumen

Los datos de sensores remotos de Radiómetros Avanzados de Muy Alta Resolución (AVHRR) tienen una resolución espacial poco fina (tamaño del pixel 1 km^2) y una resolución temporal muy alta, la cual puede ser utilizada para estimar regionalmente la productividad primaria neta. El indice de vegetación de diferencia normalizada (NDVI) es usado para determinar la fracción de la radiación fotosintéticamente activa absorbida, la cual es sensitiva a diferencias de crecimiento causadas por grandes variaciones de precipitación entre años. El promedio de 12 años de la producción primaria neta fue usado para calcular las cargas animal en unidades-animal-mes por acre para el estado de Wyoming. Las cargas animal también fueron calculadas para Wyoming a partir de capas geoespaciales de suelo y clima a una escala de 1:500 000 basadas en las cargas animal del Servicio de Conservación de los Recursos Naturales del Departamento de Agricultura de los Estados Unidos, *Technician Guide to Range Sites and Range Condition*. En una comparación de pixel por pixel hubo correlación débil, pero significativa, entre los dos métodos basados en la distribución espacial de la precipitación. Hubo clases de tipo de vegetación donde los datos del AVHRR predijeron las cargas animal muy bajas o muy altas. Se necesita hacer mas trabajo para reducir las incertidumbres de los datos geoespaciales para la determinación de las cargas animal a partir del NDVI y las tablas de carga animal. Los sensores remotos indican que la condición actual de la vegetación es un punto importante en el desarrollo de pronósticos regionales de la condición y tendencia del pastizal y las cargas animal proyectadas para herramientas de soporte en la toma de decisiones.

Key Words: Advanced Very High Resolution Radiometer, geographic information systems, net primary production, normalized difference vegetation index

INTRODUCTION

One of the most important indicators for rangeland health is vegetation productivity (National Research Council 1994; Pellant et al. 2000). Remote sensing has potential for monitoring rangeland production at different scales (Hunt et al. 2003). The advantage of remote sensing is that the actual production for an entire area can be estimated, which is easier and less expensive than ground sampling with small plots (Hunt et al. 2003). Whereas plant communities can be identified, a disadvantage of remote sensing is that the plant species composition is difficult to identify (Tueller 1989, 1992, 1995).

Holecheck (1988) and Holecheck et al. (1998) show how measurements of aboveground net primary production can be used to determine stocking rates in animal-unit months per acre (AUM/acre), where an animal unit is based on dry

At the start of this research, the first author was an assistant professor and the second author was an undergraduate research assistant at the Botany Dept, University of Wyoming, Laramie, WY.

Correspondence: E. Raymond Hunt Jr., USDA-ARS Hydrology and Remote Sensing Laboratory, Building 007, Room 104, 10300 Baltimore Ave, Beltsville, MD 20705-2350. Email: erhunt@hydrolab.arsusda.gov

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Table 1. Parameters for stocking rates for remote sensing by vegetation land cover class.[1]

Land cover class	ε	γ	η	υ	ϕ
Agriculture	2.25	0.45	0.91	0.50	0.50
Grass	1.13	0.48	0.21	0.50	0.15
Shrub	1.13	0.48	0.40	0.40	0.50
Conifer	1.50	0.50	0.85	0.40	0.75
Deciduous	1.15	0.50	0.35	0.50	0.75
Tundra	0.75	0.45	0.25	0.30	0.15

[1] ε indicates radiation use efficiency for gross primary production ($g \cdot MJ^{-1}$); γ indicates autotrophic respiration losses of gross primary production (fraction); η indicates allocation of net primary production aboveground (fraction); υ indicates utilization of key species (fraction); and ϕ indicates nonusable forage (fraction).

matter intake of 20 pounds (9.1 kg) per day for 1 mature cow. Furthermore, the adjustments to the stocking rate are based on slope and distance to water, which are commonly available as geospatial data. Thus, with minimal changes to the method described by Holecheck (1988), stocking rates can be determined from remotely sensed and other geospatial data (Hunt et al. 2003).

How good are estimates of remotely sensed stocking rates? Other commonly available geospatial data include soils, climate, and land cover, which are essential inputs for determining stocking rates using the US Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) *Technician Guide to Range Sites and Range Condition* (which was recently replaced by ecological site descriptions). We compare the regional stocking rates for the state of Wyoming, determined by 1) remotely sensed data, and 2) scaling up the NRCS guides using other geospatial data. Some agreement between the 2 methods is expected, because vegetation productivity is highly correlated with precipitation. However, differences between the 2 methods will show 1) errors in the geospatial data, 2) model errors, or 3) areas where the actual vegetation condition is not in good condition.

Background

Normalized difference vegetation index (NDVI) was originally developed to enhance detection of vegetation and to reduce effects of atmospheric transmittance, topography, and solar elevation and azimuth (Rouse et al. 1974). For satellites, NDVI is defined:

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{Red})/(\mathrm{NIR} + \mathrm{Red}) \quad [1]$$

where NIR is the apparent spectral reflectance from a near-infrared band and Red is the apparent spectral reflectance from a red band. The wavelength intervals for each band are sensor-dependent. Satellite and airborne sensors measure the spectral radiance from a pixel ($mW \cdot nm^{-1} \cdot m^{-2} \cdot sr^{-1}$), where the land surface area covered by pixel is also sensor-dependent. Corrections for atmospheric transmittance and solar elevation and azimuth are applied to obtain apparent spectral reflectance (Eidenshink 1992). NDVI is correlated to many plant variables such as leaf area index, biomass, and cover (Curran 1983; Baret and Guyot 1991; Anderson et al. 1993; Carlson and Ripley 1997). Subsequently, Asrar et al. (1984), Hatfield et al. (1984), and others showed that NDVI was approximately equal to the fraction of absorbed to incident photosynthetically active radiation (f_{APAR}, dimensionless). Absorbed photosynthetically active radiation (APAR, $MJ \cdot m^{-2} \cdot d^{-1}$) is estimated by the product of NDVI and daily incident PAR ($MJ \cdot m^{-2} \cdot d^{-1}$). Corrections can be made to more accurately estimate f_{APAR} from NDVI (Goward and Huemmrich 1992; Myneni and Williams 1994). Often, APAR is approximated by photosynthetically active radiation intercepted (not absorbed) by the canopy (Prince 1991; Running and Hunt 1993; Gower et al. 1999).

Advanced very high resolution radiometer (AVHRR) NDVI data are most often used for regional monitoring because the pixel size is large (1 km^2). These data are collected daily and composited over a short period—weekly or biweekly—to generate nearly cloud-free images from which the change in f_{APAR} over a growing season may be determined (Eidenshink 1992). AVHRR NDVI shows the spatial distribution of vegetation response to changes in precipitation over large areas (Di et al. 1994; Liu and Kogan 1996; Yang et al. 1998; Ji and Peters 2003). With the launch of the National Aeronautics and Space Administration's Terra satellite in December 1999 and Aqua satellite in May 2002, the Moderate-Resolution Imaging Spectrometer (MODIS) is now providing improved estimates of f_{APAR} because of better sensor calibration and atmospheric corrections (Reeves et al. 2001). The Vegetation sensor onboard the Systèm pour d'Observation de la Terre (SPOT) satellite is also being used to estimate f_{APAR} (Wylie et al. 2002). However, these sensors do not have the long-term, continuous record of AVHRR.

Radiation use efficiency (ε, $g \cdot MJ^{-1}$) is the amount of dry matter gained per unit APAR (Montieth 1977; Kumar and Montieth 1981; Sinclair and Muchow 1999; Kiniry et al. 1999; Nouvellon et al. 2000, 2001). Following the report by Ruimy et al. (1995), gross primary production (GPP, $g \cdot m^{-2} \cdot y^{-1}$) is defined as follows:

$$\mathrm{GPP} = \varepsilon \sum \mathrm{APAR} \quad [2]$$

summed for each biweekly period over the year. Moreover, ε is often defined on the basis of either net primary production or aboveground net primary production, so ε depends on the amount of plant respiration and allocation between roots and shoots, respectively (Prince 1991; Hunt and Running 1992; Running and Hunt 1993; Ruimy et al. 1994; Prince and Goward 1995; Goetz and Prince 1999; Gower et al. 1999; Hunt et al. 2004). Net primary production (NPP, $g \cdot m^{-2} \cdot y^{-1}$) is defined as:

$$\mathrm{NPP} = (1 - \gamma)\ \mathrm{GPP} \quad [3]$$

where γ is the fraction lost to autotrophic respiration. Aboveground net primary production (ANPP, $g \cdot m^{-2} \cdot y^{-1}$) is defined as:

$$\mathrm{ANPP} = \eta\ \mathrm{NPP} \quad [4]$$

where η is the fraction allocated above ground. In this study, respiration and allocation are determined by land cover class (Table 1).

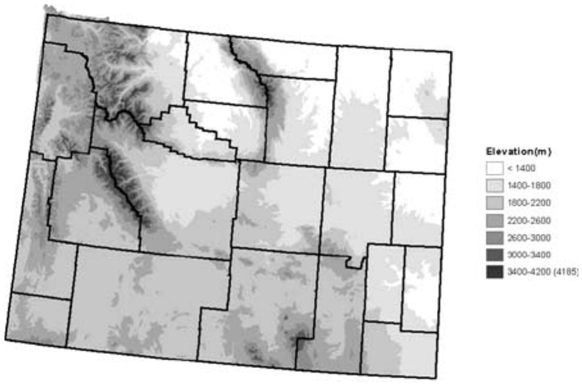

Figure 1. Elevation data for Wyoming. The data were 30-m digital elevation model data aggregated to 1-km^2 pixels.

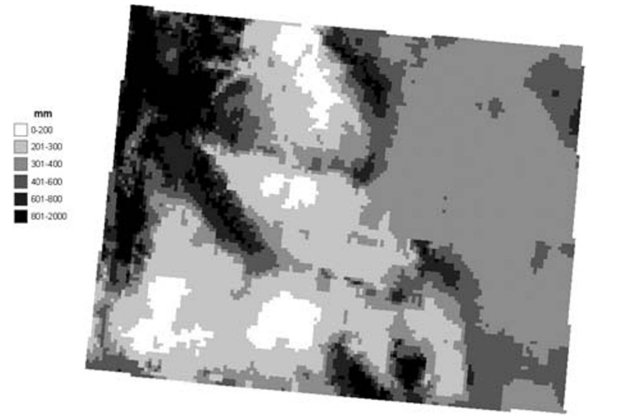

Figure 2. Average annual precipitation for Wyoming from the Parameter-Elevation Regressions on Independent Slopes Model data.

Available forage (AF, $g \cdot m^{-2} \cdot y^{-1}$) is less than ANPP, because some of the ANPP measured for a pixel is from vegetation that is not usable by livestock, such as invasive weeds, tree foliage, and woody stems. Furthermore, only some of the forage that is potentially available to livestock should be utilized to maintain plant community composition (Holecheck et al. 1998). Therefore:

$$AF = \upsilon(1 - \phi)ANPP \quad [5]$$

where υ is the desired utilization fraction of the key species and ϕ is the fraction of nonusable forage. Parameters for available forage (υ, ϕ) are determined by plant community type in the field, which is approximated by remotely sensed land-cover class (Table 1).

METHODS

Stocking Rates From Geospatial Data

Digital elevation data (Wyoming Geographic Information Science Center 2004a; Fig. 1) were used to determine slope, where the median slope for each 1-km^2 grid cell was determined from 30-m grid cells (n = 1 156). Average precipitation for the years 1971 to 1990 (Fig. 2) were obtained from the output of the Parameter-Elevation Regressions on Independent Slopes Model (PRISM; Daly et al. 1994; US Department of Agriculture Natural Resources Conservation Service 1999). The Major Land Resource Area (MLRA) boundaries (Fig. 3) were obtained from the US Department of Agriculture Natural Resources Conservation Service (1997) and converted to 1-km^2 grid cells using a majority decision rule. Precipitation and MLRA boundaries are spatially correlated to elevation. Soil series geospatial data at a scale of 1:500 000 (Munn and Arneson 1998; Wyoming Geographic Information Science Center 2004b) were converted to soil texture classes (Larry C. Munn, personal communication, April 1998), and aggregated into 1-km^2 grid cells using a majority decision rule. The US Department of Agriculture Natural Resources Conservation Service *Technician Guide to Range Sites and Range Condition,* with initial stocking rate tables, was obtained for each MLRA in Wyoming. The stocking rates for "good" range condition were made into a lookup table, so each 1-km^2 grid cell was assigned a stocking rate on the basis of MLRA, precipitation, and soil texture class.

All geospatial and remotely sensed data were displayed as a Lambert Azimuthal Equal Area projection using a spherical Earth of radius 6 370 997 meters. The latitude of the map origin was 45° North and the central meridian was 100° West.

Stocking Rates From Remote Sensing

AVHRR data for the state of Wyoming were acquired from the US Geological Survey Earth Resources Observations and Science Data Center (Sioux Falls, South Dakota) for 1989 through 2000. These data are identical to the Conterminous US AVHRR Data Sets (Eidenshink 1992), with the exception that the AVHRR composites for 1998 to 2000 were made weekly instead of biweekly. The AVHRR data were checked for subpixel cloud contamination, because cloud-top temperatures are cold, and cold land-surface temperatures indicate cloud contamination. Land-surface temperature was calculated using AVHRR bands 4 and 5 (Price 1984), and if the temperatures during the growing season were lower than −20°C, then NDVI for that compositing period was determined by a linear interpolation of uncontaminated NDVI from periods before and

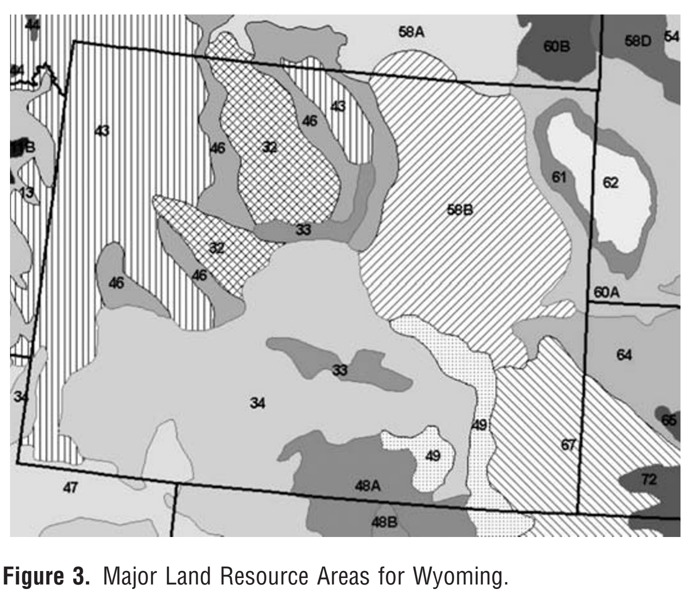

Figure 3. Major Land Resource Areas for Wyoming.

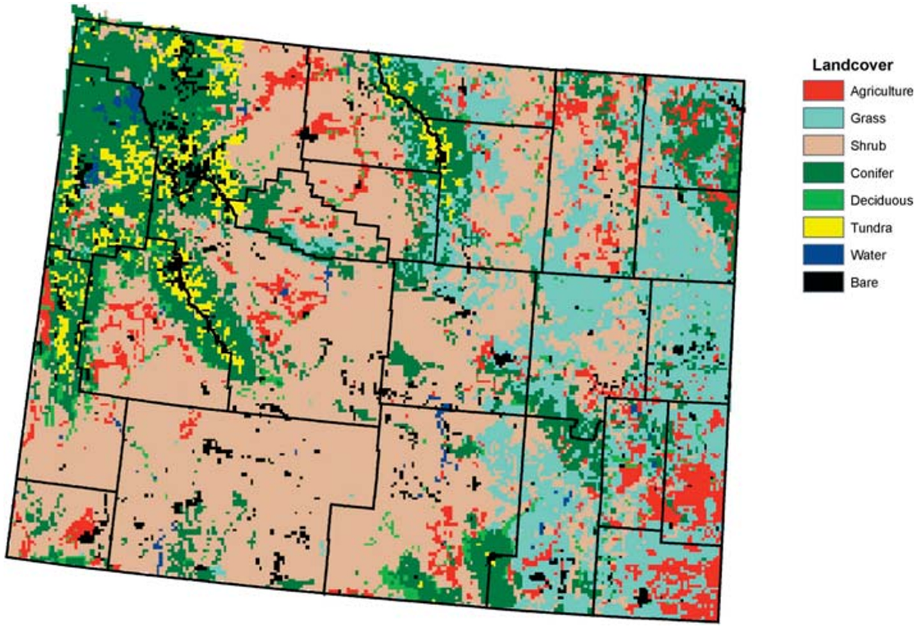

Figure 4. Wyoming gap land cover data. These data were developed by Driese et al. (1997) and aggregated into 1-km^2 pixels to match the Advanced Very High Resolution Radiometer data.

after. Wintertime NDVI data were often not available, so GPP was assumed to be zero.

The Wyoming Gap land cover data (Driese et al. 1997; Wyoming Geographic Information Science Center 2004c) were used to determine the vegetation type (Table 1) occurring in each 1-km^2 pixel using a majority decision rule (Fig. 4). Vegetation type was used to determine the parameters in Equations 2–5 for each pixel (Table 1). Allowable forage utilization (υ) was determined from data reported by Holecheck et al. (1998) and allocation aboveground (η) was determined from data reported by Jackson et al. (1996). Nonusable forage (ϕ) was estimated from community composition accounting for GPP from trees and shrubs. Autotrophic respiration losses (γ) were modeled according to the report by Hunt et al. (1996). Radiation use efficiency (ε) was determined from data reported by Hunt and Running (1992) for conifer and deciduous forests, by Hunt et al. (2004) for grasslands and shrublands, and by Prince (1991) and by Running and Hunt (1993) for agriculture.

AVHRR NDVI data were used to estimate f_{APAR} with corrections for the average snow-free minimum and maximum NDVI for the entire state:

$$f_{\mathrm{APAR}} = 1.25\ \mathrm{NDVI} - 0.10 \qquad [6]$$

(Hunt et al. 2004). Daily precipitation and temperature data for 1989 to 2000 were obtained from 15 National Oceanographic and Atmospheric Administration National Weather Service meteorological stations distributed around Wyoming. Incident solar irradiances ($\mathrm{MJ \cdot m^{-2} \cdot day^{-1}}$) were calculated daily from the temperature and precipitation data (Winslow et al. 2001), and multiplied by the fraction of PAR to solar radiation (measured to be 0.44 ± 0.04; Hunt et al. 2004). GPP was calculated daily for 1989 to 2000 (Eq. 2), and summed into annual totals. Mean annual GPP was used to determine available forage (Eqs. 3–5).

Holecheck's (1988) method for calculating stocking rates reduces available forage based on slope and distance to water. There is no reduction in stocking rate for slopes from 0% to 10%; there is a 30% reduction for slopes 11%–30%, and there is a 60% reduction for slopes 31%–60%. Because of the large pixel size and small map scale, distances to water could not be calculated accurately, so we assumed no reduction of stocking rate based on distance to water.

RESULTS AND DISCUSSION

The stocking rates from the NRCS *Technician Guide to Range Sites and Range Condition* vary from 0 to 2 AUM/acre (Fig. 5). Areas with 0 AUM/acre are located in the cold desert shrublands (Fig. 4) with low rainfall (Fig. 2). Nearby are areas with 2 AUM/acre, which were located on subirrigated soils. Generally, the shrublands of central Wyoming have stocking rates of 0.01 to 0.3 AUM/acre, grassland areas in eastern Wyoming have stocking rates of 0.3 to 0.5 AUM/acre, and forested areas in the mountains (Fig. 4 and Fig. 1, respectively) have stocking rates of 0.5 to 0.9 AUM/acre (Fig. 5).

Averaged over 12 years from 1989 to 2000, remotely sensed NPP ranged from $\leq 300\ \mathrm{g \cdot m^{-2} \cdot y^{-1}}$ in the cold desert shrublands to $\geq 1\,700\ \mathrm{g \cdot m^{-2} \cdot y^{-1}}$ in the montane forests. The spatial pattern of NPP for Wyoming is similar to the land cover (Fig. 4) and NRCS stocking rates (Fig. 5), because the primary variable affecting stocking rate is precipitation (Fig. 2), which in turn is strongly related to elevation (Fig. 1). Year-to-year variability in NPP is large particularly for the grasslands in eastern Wyoming, because of the year-to-year variability in precipitation. Thus, the long time series of AVHRR data is important for obtaining reasonable averages of GPP and NPP. Other sensors such as MODIS and SPOT vegetation have been in orbit for a relatively short time; the data from these sensors

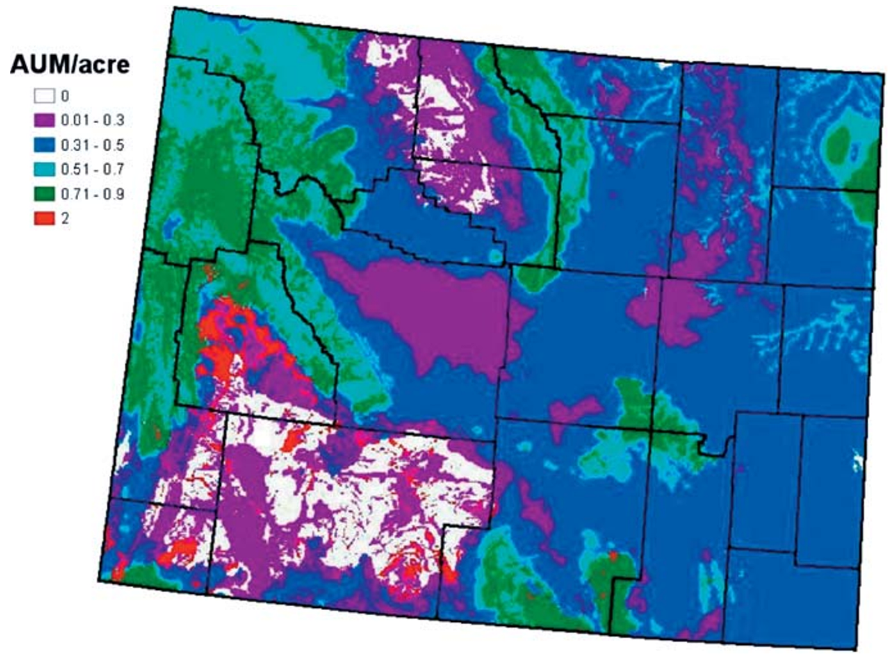

Figure 5. Stocking rates (animal-unit months [AUM]/acre) from NRCS *Technician Guide to Range Sites and Range Condition* based on major land resource area, precipitation, and soil texture class.

must be adjusted to match the characteristics of AVHRR to obtain statistically valid, long-term averages (Gitelson and Kaufman 1998).

The calculated stocking rates from the AVHRR data (Fig. 6) have a much higher range than do the stocking rates from NRCS tables and geospatial data (Fig. 5). Some of the highest stocking rates from the AVHRR data are along major rivers and in southeastern Wyoming (Fig. 6). From the land cover classifications (Fig. 4), these areas are agricultural, showing the remotely sensed stocking rates are sensitive to the actual vegetation conditions, even when the vegetation is not used for livestock. Many of the grassland areas in eastern Wyoming have higher calculated stocking rates (Fig. 6) than expected based on the NRCS tables (Fig. 5). However, the shrublands in central and western Wyoming have uniformly low stocking rates (Fig. 6), similar to the NRCS tables (Fig. 5).

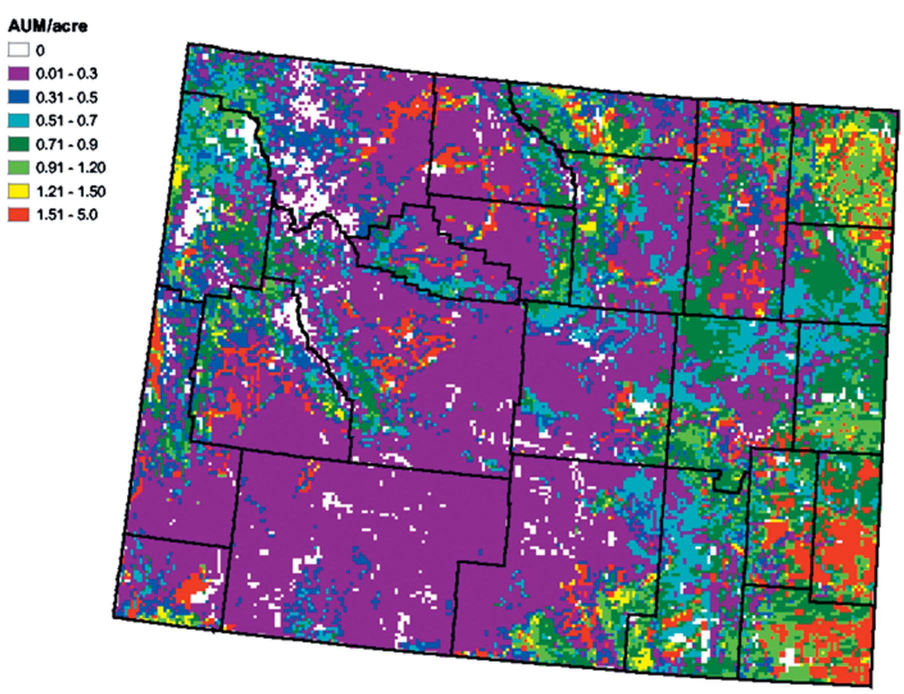

Figure 6. Average stocking rate (animal-unit months [AUM]/acre) from Advanced Very High Resolution Radiometer normalized difference vegetation index for the state of Wyoming.

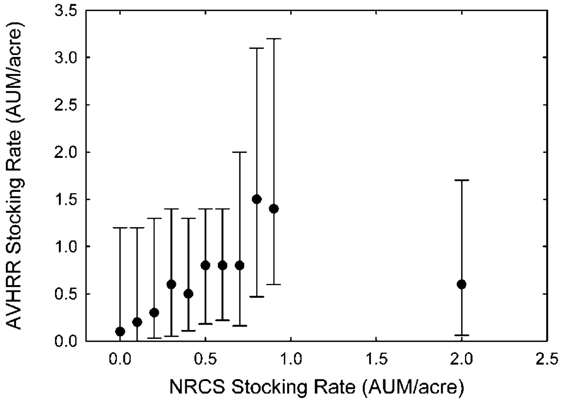

Figure 7. Comparison of Advanced Very High Resolution Radiometer (AVHRR) stocking rate and Natural Resources Conservation Service (NRCS) stocking rate for each 1-km^2 pixel. Because of the large number of points, for each NRCS stocking rate, the median of the AVHRR stocking rates is the point, and the range represents the 10th and 90th percentiles. The NRCS stocking rate of 2 animal-unit months (AUM)/acre are located in areas characterized by subirrigated soils.

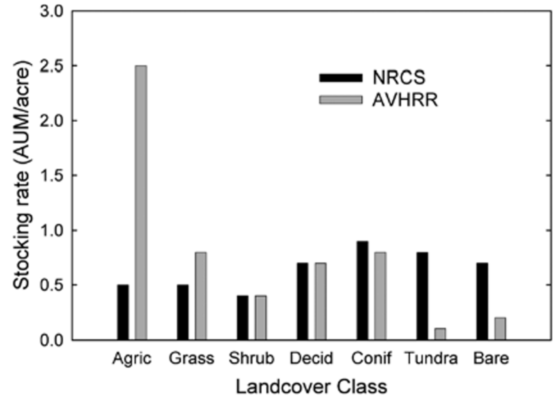

Figure 8. Median values of the Advanced Very High Resolution Radiometer (AVHRR) and Natural Resources Conservation Service (NRCS) stocking rates by land cover class.

For any given stocking rate for good vegetation condition from the NRCS *Technician Guide to Range Sites and Range Condition,* there is a large range of stocking rates determined by the AVHRR data over the entire state (Fig. 7). The median values of the AVHRR stocking rates are about 50% higher than the recommended NRCS stocking rate, when the NRCS stocking rate is $<$ 1.0 AUM/acre (Fig. 7). However, when the NRCS stocking rate is 2.0 AUM/acre, the median value of the AVHRR stocking rate is only 0.6, and the 90th percentile is 1.7 AUM/acre. The high values of NRCS stocking rates are from areas with subirrigated soils. The lower stocking rates calculated from AVHRR data (Fig. 7) suggest that the total area of subirrigated soils may be smaller than indicated by the soil data layer. This is further evidence that NDVI stocking rates are indicating actual vegetation conditions, because the high productivity found on subirrigated soils is averaged with lower productivity on adjacent soil types.

When the stocking rates are aggregated according to land cover class, the regional differences between the median AVHRR stocking rates and the median NRCS stocking rate become more apparent (Fig. 8). The median AVHRR stocking rate for agricultural areas is much higher than the median NRCS stocking rate, because the NRCS tables were extrapolated on the basis of soil series and not land cover type. On the other hand, areas that are classified as alpine tundra and bare soil have much lower AVHRR stocking rates compared to the NRCS stocking rates (Fig. 8). The discrepancy for alpine tundra may be from the tables used (high alpine meadows with annual precipitation $>$ 510 mm). Unvegetated areas (urban, coal mines, bare rock, sand dunes) were, in large part, not identified on the soil series map, and would not be associated with good range condition.

The median AVHRR stocking rate for grasslands is about 50% higher than the NRCS stocking rates (Fig. 8). Of the parameters in Table 1, the best known is the radiation use efficiency (see Eq. 1), because it can be determined from CO_2 flux data (Ruimy et al. 1995; Hunt et al. 2004) or direct measurements (Nouvellon et al. 2000, 2001). There are many sites with CO_2 flux measurements that are part of the Rangeland Carbon Dioxide Flux Project (Svejcar et al. 1997). One of the problems with this study is that a constant ε was used for a given land cover type, whereas ε for a single species may vary several-fold due to weather and site-specific variables (Hunt and Running 1992; Running and Hunt 1993). Reduction of ε by about 50% for grasslands could be justified by the range of likely ε and would eliminate most of the differences between the AVHRR and NRCS stocking rates. Adjustment of model parameters (i.e., "tuning") may be required for some highly uncertain parameters (such as η and ϕ in Table 1), but the adjustments may create problems when the model is used to predict stocking rates in other states.

A problem with using large 1-km^2 pixels is that each pixel is a mixture of sites with good forage and sites with little or no forage. It is extremely difficult to test calculations of stocking rates using ground measurements over such large pixels. If the relationship between NDVI and f_{APAR} is approximately linear (Goward and Huemmrich 1992; Myneni and Williams 1994), then pixel GPP is a spatially weighted average of the GPP on the ground. If a pixel shows that the stocking rate is 1.0 AUM/acre, but the rancher and range conservationist know that the stocking rate for a specific pasture in that pixel is say 2.0 for subirrigated soils, then the other areas in that pixel must have a stocking rate lower than 1.0 to obtain the spatially weighted average. Furthermore, grasslands are interspersed with draws and riparian zones that have higher productivity, causing pixel productivity and stocking rate to be higher than measured by representative small plots located between the draws, accounting for the 50% greater stocking rates found in grasslands by remotely sensed data (Fig. 8). Both the AVHRR and NRCS stock-rate calculations do not adequately account for the contributions of small, productive areas within the 1-km^2 pixel or grid cell, respectively. On the other hand, low values of remotely sensed stocking rates are usually indicative of the actual vegetation conditions on the ground.

A more subtle set of errors may be from the boundary location of geospatial data. Boundary locations are difficult to define because of gradual change from one class to the next. Peleg and Anderson (2002) found that for 2 images of the same field, small errors in location created large statistical variation and caused the r^2 to be low. These errors may be even larger in this study because we used multiple independent geospatial data sources for calculations of both AVHRR and NRCS stocking rates. Remote sensing data with higher spatial resolution (Landsat Thematic Mapper) and geospatial data with larger map scale will not necessarily produce better results, because more classes will be identified and the larger number of boundaries will increase uncertainty. Therefore, regional averages for stocking rates by remote sensing may be more appropriate than the value of a single pixel or grid cell.

MANAGEMENT IMPLICATIONS

This study took an important step required to apply remotely sensed data for rangeland management by calculating stocking rates from AVHRR NDVI. Previous studies ended at the determination of net primary production.

Whereas the maps of stocking rates presented here are not yet ready for management use, we made substantial progress. A goal of remote sensing is to provide an independent assessment of the actual vegetation condition, which changes over time due to management, climate, invasive species, and other factors. Because the appropriate scale of the data is regional, remote sensing will provide important information on range condition, trends, and projected stocking rates for county, state, and national management plans and be incorporated into decision support tools for individual grazing allotments.

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