Monitoring grasslands from outer space: is the pixel replacing the quadrat?

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Grasslands in peril

Grasslands are the largest of the earth's four major vegetation types and are among the most agriculturally productive lands in the world. Approximately one-quarter of the earth's land surface is covered by grass species, which can be found on every continent except Antarctica.

The tallgrass prairie ecosystem of the North American Great Plains is among the most biologically diverse of all grasslands, but since the mid-1800s, they have been highly fragmented by their conversion to cropland and the introduction of non-native grasses into pastures for cattle grazing (Sims, 1988). It is estimated that only 1% of all native prairies still exist in the plains of North America (Risser, 1988; Steiger, 1930). Prairie species composition and biological function are differentially altered by fragmentation and various land-use practices (Weaver, 1968; Collins, 1992; Gibson *et al*., 1993; Briggs and Knapp, 1995; Turner and Knapp, 1996; Collins and Steinauer, 1998). Examples of prairie land-use practices include various combinations of grazing by livestock and wildlife, haying, burning, and revegetation activities. The alteration of prairie biophysical properties also influences surface and subsurface hydrology, plant and animal diversity, and biogeochemical fluxes, as well as, and maybe most importantly, the way the land can be used in the future.

Most remaining grasslands of the central Great Plains are dominated by introduced cool-season (C_3) grass species, such as smooth brome (*Bromus inermis*) and tall fescue (*Festuca arundinacea*). In addition, grassland fragmentation and aggressive wildfire suppression have all but eliminated natural wildfire events within the Great Plains, which is also true for many other grassland ecosystems of the world. The lack of periodic wildfires in the Great Plains has allowed deciduous and evergreen trees to invade onto lands once dominated by grasses. A recent study by Hoch (2000) in eastern Kansas showed that areas of wooded pasture have more than doubled in 13 years. This invasion resulted in an areal and volumetric woodland increase of 210% and 154%, respectively, by red cedar (*Juniperus virginiana*). Similar invasion rates by various juniper species are common throughout most of the arid and semi-arid regions of the western United States (West, 1984; Tausch *et al*., 1981).

While most land-use changes in the Great Plains have been at the expense of the native grasslands, an interesting reverse on this practice was promoted by the US Conservation Reserve Program (CRP), which paid land owners $19.5 billion to convert 14.8 million hectares of croplands, on highly erodible soils, back to grassland, woodland, and other conservation uses between 1986 and 1995. In Kansas, during this period, total grassland increased by 18% as a result of the CRP. In some Kansas counties, 25% of the cropland (maximum permitted) was converted to CRP, with most of these lands being planted back to native tallgrass species (US Farm Service Agency, 1997). Very likely, the US CRP represents the most extensive and rapid human-induced land-cover and land-use change in the history of the world; and yet many individuals are unaware of this program and its impacts upon ecosystems throughout the United States.

Despite land management practices and government programs that have major impacts on grasslands and despite the importance of preserving the endemic plant and animal species of the temperate grasslands, these lands receive very low levels of protection. According to the Grasslands Conservation Council of British Columbia (2003):

> The temperate grasslands of the world, known variously as the prairie in North America, the pampas in South America, the steppes in eastern Europe and northern Eurasia and the grassveld in South Africa, are among the most diverse and productive of all the earth's terrestrial biomes. Yet, without exception, temperate grasslands have received very low levels of protection. According to the 1997 United Nations List of Protected Areas, only 0.69% of the temperate grasslands biome is under some kind of protective status. This protection level ranges from a low of 0.08% in the Argentine pampas to very modest highs of 2.01% in the lowland grasslands of south-eastern Australia and 2.2% in the South African grassveld.
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> This protection level is not only the lowest of the globe's 15 recognised biomes, but is the lowest by several orders of magnitude. Tropical grasslands and savannas, for example, enjoy a level of protection nine times higher than their temperate cousins. Temperate broad-leaf and needle-leaf forests receive protection levels six and eight times higher than grasslands, respectively. Temperate subtropical forest, over which so much justifiable concern has been expressed, receive 14-fold greater protection worldwide than do temperate grasslands.

The Great Plains region of the United States represents one of the most vulnerable agro-ecosystems (an ecosystem with significant agricultural influence) in the American northern hemisphere. Wide annual and inter-annual variations in weather strongly influence crop and rangeland production (Rosenzweig, 1997). Many of the key issues that relate to the functioning of the Great Plains agro-ecosystem are directly tied to broad issues identified by the US Global Climate Change Research Program (USGCRP), particularly in agriculture, which includes croplands and grasslands. Drawing on discussions arising out of the Central Plains workshop of the USGCRP, the following issues were identified as critical to this Great Plains region (note, however, that these issues are common to many other parts of the world as well): (1) protecting and monitoring crop production and yield, (2) assessing grassland condition and productivity, (3) monitoring land-use/land-cover change, (4) modelling soil erosion and conservation practices, (5) evaluating water consumption and quality, (6) modelling wildlife habitat, and (7) evaluating socio-economic impacts of short- and long-term land-cover and land-use change.

Note that six of the seven key issues listed above are influenced by the way grasslands are managed or mismanaged. In Kansas, 39% of the state is classified as grassland (Kansas Applied Remote Sensing, 2002). Until recently, this percentage was unknown. Even in developed countries, accurate and timely maps of current vegetation types and trends are nearly always lacking. This is because many resource managers are still trying to make large-area land resource management decisions based on data collected from a 1.0-m^2 quadrat (sampling frame). According to Dr Edward A. Martinko, former director of the US Environmental Monitoring and Assessment Program (EMAP) for the Environmental Protection Agency, as of 1993, 80% of all ecological monitoring and assessment measurements were made using a 1.0-m^2 or lesser sized sampling unit (quadrat) (pers. com., 2003). We frequently hear of the challenges of scaling up from the local to the regional and continental scales. Obviously, this scaling-up challenge will continue to plague scientists and resource managers if we continue to make most of our environmental measurements using a 1.0-m^2 quadrat. Those who persist in using only the small sampling unit for measuring biotic and abiotic factors will eventually find themselves unable to contribute to the understanding of ecosystem-, continental-, and global-scale earth system processes, which is fast becoming the field of study where more research financial support is being placed each year.

Grassland ecosystems are dynamic, and the climate- and human-induced processes that modify them operate across numerous spatial and temporal scales. Understanding of plant response to weather patterns and land management practices is fundamental to most aspects of resource management and ecosystems modelling. To better understand plant response to varying environmental conditions, we must be able to characterise multiple biophysical (e.g., biomass, cover, leaf area, density, etc.) and biochemical (e.g., nitrogen and other nutrients, chlorophyll, etc.) factors at multiple spatial and temporal resolutions. If we are ever going to successfully address these multiple scaling issues, we must look for new methods for characterising critical biological factors.

Remote-sensing systems and resolutions

With increasing frequency, scientists and land resource managers are using earth observation measurements, made using airborne and space-borne remote-sensing instruments. Since the early 1970s when the first earth-orbiting, land-observation satellite, now called Landsat, was deployed in outer space, over two dozen remote-sensing instruments have been launched by various nations around the world. Terra, Latin for land, is the name of the earth-observing system (EOS) flagship satellite, launched on 18 December 1999. The five sensors aboard Terra are comprehensively measuring our world's climate system to observe and measure how earth's atmosphere, cryosphere, lands, oceans, and life all interact. Data from this mission are used in many research and commercial applications. Terra is a vital part of NASA's Earth Science Enterprise, helping us understand and protect our planet (http://terra.nasa.gov). Private commercial satellite systems have also been launched in recent years. The spatial resolution of these private systems is around 1 m^2/pixel. To see impressive examples of these high spatial resolution data, you can visit the web sites of DigitalGlobe for examples of their QuickBird imagery (www.digitalglobe.com) or Space Imaging for examples of their Ikonos imagery (www.spaceimaging.com).

Although the high *spatial resolution* imagery of the new, commercially available satellites is very impressive and intriguing to view, one should know that spatial resolution is only one of the four resolutions that should be considered when selecting remotely sensed data. The other resolutions include *spectral* (number of wavelengths or size of the bandwidth measured), *radiometric* (number of energy levels that the sensor can detect, and *temporal* (number of observations or overflights the satellite makes within a unit of time). Unfortunately, the relationship among these four resolutions is inverse, meaning that, as one resolution in increased, another resolution must be decreased. For example, as pixel size gets smaller (i.e., spatial resolution increases), temporal resolution deceases.

I often find myself explaining to those who wish to map land cover over large areas that the high spatial resolution data are expensive to purchase and that the computer processing of these data over large areas is time consuming. It seems that those who are new to remote sensing are easily convinced that being able to see fine spatial detail on an image is most important. This might be true if you wish to count cows, but if your objective is to map and monitor grassland types and conditions over large areas, coarser resolution imagery is usually more desirable. When I am mapping rangeland types, I am not normally interested in mapping every ant hill or small patch of bare ground. Using an image with coarser spatial resolution (bigger picture elements, or 'pixels'), such as 20 or 30 m^2/pixel, can produce better results for mapping grasslands over large areas than using the metre or submetre resolution.

During my 22 years of research in using remotely sensed data for mapping rangeland vegetation, I have generally found that greater temporal resolution is more important than having smaller pixels, more bands, or improved radiometric resolution. Considerable remote-sensing research has also focused on the development of vegetation indices (wavelength combinations that are designed to improve one's ability to discriminate between photosynthetically active vegetation types and dead vegetation or nonvegetation types). During my studies, however, I have not found that the use of any one vegetation index gave me a significant advantage over another.

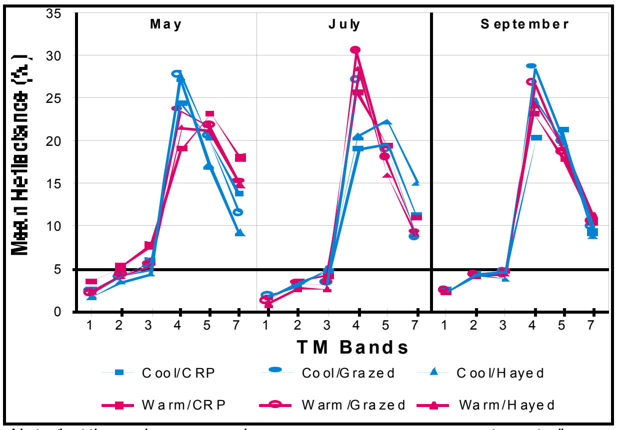
My research in the use of hyperspectral datasets and analysis techniques (analysis of many spectral wavelengths or bands, often hundreds) for discriminating among grassland types has produced very promising results. Unfortunately, the use of hyperspectral datasets over large areas is not practical at this time. There is only one space-borne hyperspectral sensor, called Hyperion, which is part of NASA's New Millennium Program, Earth Observing-1 Satellite (NMP EO-1). This system collects 220 bands within the spectral region of 0.48 to 2.35 µm. The radiometric resolution is 16-bit, or 65,536 potential brightness values per pixel; and each image is 7.7 km wide and 42 km long, creating an image computer file size of approximately 400 megabytes. Hyperion is classified as a research system; therefore, it has limited utility as a grassland mapping and monitoring system at this time. For more information about Hyperion, including acquisition of the data, refer to http://eo1.usgs.gov.

One of my graduate students and I are investigating the use of the HyMAP (a 128-band hyperspectral sensor operated by HyVista located in Australia (hvc@hyvista.com)). Key questions in the Great Plains are (1) can hyperspectral imagery and analysis approaches be used to discriminate among subtle differences in grassland management practices and (2) can advanced hyperspectral analysis approaches be used to identify compositional mixtures of C_3 (cool-season) and C_4 (warm-season) grasses.

Our preliminary findings are that these hyperspectral data are useful for discriminating among subtle differences in grassland life-forms (C_3 and C_4 grasses) and paddock management practices, such as grazing and haying. Unfortunately, like Hyperion, the use of these data is not practical at this time for grassland mapping and monitoring over large geographic areas. While it is now impractical to use airborne hyperspectral imagery over an entire region, fundamental questions about the utility of these data for quantifying biophysical and chemical properties of grasslands should be explored now so that, as hyperspectral data from earth-orbiting satellites become more readily available, we are able to more effectively address grassland management issues.

Discriminating among grassland types using multitemporal analysis

Over the last 10 years, my students' and my research has demonstrated the value of incorporating a multitemporal component into our remote-sensing datasets (Price *et al.*, 1996; Guo *et al.*, 2000). This component has proven especially effective for discriminating among plant life-forms with different phenology growth patterns (eg., cool-season (C_3) versus warm-season (C_4) grasses) (Figure 1).

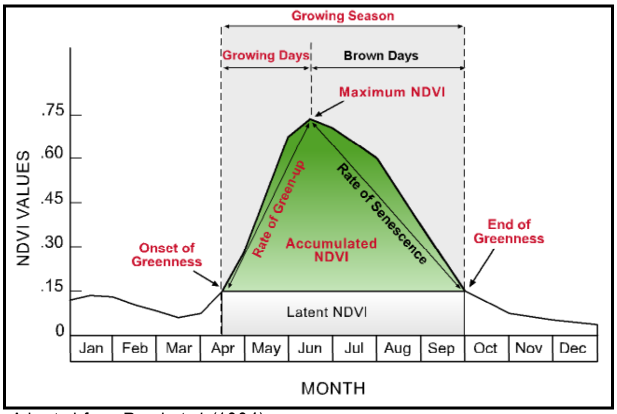


Note that the cool-season and warm-season grasses are most spectrally distinct in May and July and that the near infrared band (band 4) is the best wavelength for discriminating among the grassland types (Guo *et al.*, 2000).

Figure 1. Spectral reflectance curves for cool- (blue line) and warm-season (red line) grasses under grazing, haying, and US CRP land management practices.

Confounding factors for discriminating among grassland types are being resolved through the use of high-temporal, remote-sensor datasets and time-series analytical methods that derive measurements of plant phenological development stages (Reed *et al.*, 1994, 1996; Tieszen *et al.*, 1997). In 1989, EROS Data Center in Sioux Falls, South Dakota, USA, began producing near cloud-free, advanced very high resolution radiometer (AVHRR), biweekly, maximum normalised difference vegetation index (NDVI) composite images (Eidenshink, 1992). Because these AVHRR datasets go back to 1989, baseline spectral characteristic for vegetation can be established and used to assess temporal changes in plant biophysical properties (i.e., % change in biomass and productivity). These biweekly composites have been used to study the temporal development (phenology) of vegetation types (Reed *et al.*, 1994; Lee *et al.*, 2002; Yu *et al.*, 2003a; Yu *et al.*, 2003b). Temporal profiles derived from close-range spectroradiometer data, as well as the NDVI composites, show that the relative abundance of cool- and warm-season grasses (C_3 and C_4, respectively) can be discerned with a high degree of accuracy (Tieszen *et al.*, 1997).

Figure 2 shows a temporal profile of NDVI values for a hypothetical vegetation type. Three important plant phenological stages are shown on the graph: onset of, end of, and maximum greenness. The establishment of these three 'end-points' is critical to the estimation of the remaining nine vegetation phenology metrics (VPMs). Reed *et al.* (1996) used the onset of greenness to discriminate among vegetation types with different emergent periods. 'Duration' of greenness is the time between onset and end of greenness. This metric is used to estimate accumulation (net primary production) of green biomass. The 'range' of greenness is defined as the perpendicular line between maximum greenness and the line between onset and the end of greenness (Figure 2). This metric is influenced by plant cover types, management practices, and climate variation. 'Accumulated' greenness is a measure of the integrated NDVI values from onset to the end of greenness. This metric is another measure of biophysical response of plants to their growing conditions over the growing season.



Adapted from Reed *et al.* (1994).

Figure 2. A diagram of a hypothetical 12-month NDVI multitemporal vegetation response curve for native vegetation that is typical of the Great Plains region, USA. Shown on the graph are selected vegetation phenology metrics that can be extracted through the analysis of the NDVI, near cloud-free datasets.

The remaining three VPMs are 'rate of green-up,' 'rate of senescence,' and 'mean daily NDVI' (Table 1). Rate of green-up is simply the slope of the line between onset of greenness and maximum greenness. This metric could be used as an indicator of plant health and its ability to respond to varying environmental conditions. Rate of senescence is defined by the slope of the line between maximum greenness and end of greenness. It is my belief that this metric will be useful for discriminating among vegetation types (annual, perennial, life-forms, cool- vs warm-season, etc.). It should also be influenced by climate and land management practices. The mean daily NDVI (Table 1) is a measure of the average NDVI from onset to end of greenness. This metric should be responsive to all the factors influencing vegetation development.

Table 1. Twelve vegetation phenology metrics that can be derived from time-series analysis of biweekly NDVI multitemporal datasets.

Temporal metrics	Plant development state measured
Time of onset of greenness	Beginning of photosynthetic activity
Time of end of greenness	End of photosynthetic activity
Duration of greenness	Length of photosynthetic activity
Time of maximum greenness	Time when photosynthesis is maximum
NDVI-Value Metrics	**Plant development state measured**
Value of onset of greenness	Level of photosynthesis at start
Value of end of greenness	Level of photosynthesis at end
Value of maximum NDVI	Level of photosynthesis at maximum
Range of NDVI	Range of measurable photosynthesis
Derived Metrics	**Plant development state measured**
Accumulated NDVI	Net primary production
Rate of green-up	Acceleration of increasing photosynthetic activity
Rate of senescence	Acceleration of decreasing photosynthetic activity
Mean daily NDVI	Mean daily photosynthetic activity

We have already found these VPMs to be very effective for characterising winter wheat condition and yields (Kastens *et al.*, 1998). At the Kansas Applied Remote Sensing (KARS) Program, we have developed automated methods for extracting the VPMs. Yu *et al.* (2003c) describes our method for estimating the date of onset of greenness, which is the most critical metric to accurately estimate because the accuracy of the other metrics depends on correctly predicting onset date of greenness. The coarser spatial resolution of AVHRR (1.1 km x 1.1 km) imposes some limitations with respect to the use of the imagery on smaller grazing units. We are now investigating the application of our VPM derivation algorithms to the Moderate Resolution Imaging SpectroRadiometer (MODIS) 250-m x 250-m pixels. The methods and models we are developing should also be adaptable to future vegetation indices, such as the MODIS enhanced vegetation index (http://tbrs.arizona.edu/project/MODIS/evi.php).

As existing remote-sensing methods are refined and new methods developed, I am confident that earth-observation data from space-borne platforms will be increasingly used to map, monitor, and characterise biophysical properties of grasslands and other vegetation types throughout the world. Grassland ecologists and remote-sensing specialists should seek to develop collaborative research activities. Such collaboration will accelerate our understanding of ecosystem-, continental-, and global-scale earth system processes. It will also be critical as the quadrat is replaced by the pixel.

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