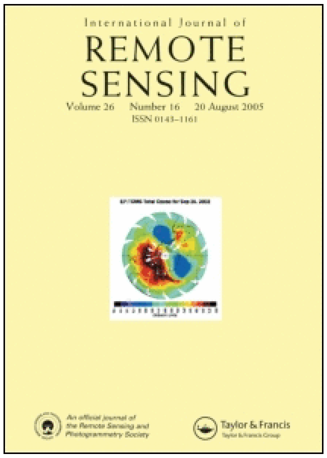

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S. E. Lobser [a]; W. B. Cohen [b]
[a] Department of Forest Science, Oregon State University, Corvallis OR 97331
[b] Pacific Northwest Research Station, USDA Forest Service, Corvallis, OR 97331

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MODIS tasselled cap: land cover characteristics expressed through transformed MODIS data

S. E. LOBSER† and W. B. COHEN*‡
†Department of Forest Science, Oregon State University, Corvallis OR 97331, USA
‡Pacific Northwest Research Station, USDA Forest Service, Corvallis, OR 97331, USA

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The tasselled cap concept is extended to Moderate Resolution Imaging Spectroradiometer (MODIS) Nadir BRDF-Adjusted Reflectance (NBAR, MOD43) data. The transformation is based on a rigid rotation of principal component axes (PCAs) derived from a global sample spanning one full year of NBAR 16-day composites. To provide a standard for MODIS tasselled cap axes, we recommend an orientation in MODIS spectral band space as similar as possible to the orientation of the Landsat Thematic Mapper (TM) tasselled cap axes. To achieve this we first transformed our global sample of MODIS NBAR reflectance values to TM tasselled cap values using the existing TM transformation, then used an existing algorithm (Procrustes) to compute the transformation that minimizes the mean square difference between the TM transformed NBAR values and NBAR PCA values. This transformation can then be used as a standard to rotate the MODIS NBAR PCA axes into a new MODIS Kauth–Thomas (KT) orientation. Global land cover patterns in tasselled cap space are demonstrated graphically by linking the global sample with several other products, including the MODIS Land Cover product (MOD12) and the MODIS Vegetation Continuous Fields product (MOD44). Patterns seen at this global scale agree with previous explorations of TM tasselled cap space, but are shown here in greater detail with a globally representative sample. Temporal trends of eight smaller-scale BigFoot Project (www.fsl.orst.edu/larse/bigfoot) sites were also examined, confirming the spectral shifts in tasselled cap space related to phenology.

1. Introduction

The tasselled cap transformation has, since its initial formulation in 1976 for Landsat Multispectral Scanner (MSS) data (Kauth and Thomas 1976), been applied as both a descriptive and analytical tool in a variety of ecological studies. E. P. Crist led a series of in-depth studies utilizing the 3-dimensional (3D) Thematic Mapper (TM) tasselled cap space for discovering patterns of vegetation and soils, including crop development (Crist 1983a,b, Crist *et al.* 1986). These investigations paved the way for utilization of the tasselled cap space for improved land cover classification (Oetter *et al.* 2001, Dymond *et al.* 2002) and estimation of attributes of landscape condition (Cohen and Spies 1992, Cohen *et al.* 1995, Skakun *et al.* 2003). Others have compared the performance of tasselled cap indices against other indices, such as the Normailzed Difference Vegetation Index (NDVI) (Todd *et al.* 1998).

*Corresponding author. Email: warren.cohen@oregonstate.edu

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The Moderate Resolution Imaging Spectroradiometer (MODIS), launched in 1999 aboard the Terra satellite, acquires data in 36 spectral bands, six of which correspond to Landsat TM bands. The tasselled cap transformation for Moderate Resolution Imaging Spectroradiometer (MODIS) data would be a valuable tool for discovering global land cover patterns, thus extending the wide range of work that has been done at the regional scale using the TM tasselled cap. Though the TM tasselled cap cannot be directly applied to MODIS given the differences in sensor design, the existence of tasselled cap features in the MODIS data space, identified by Zhang *et al.* (2002) and confirmed in this paper, affords the opportunity to develop a tasselled cap transformation for MODIS that retains the original meaning of the indices and provides continuity among sensors.

The features of brightness, greenness and wetness have been compared to a number of biophysical parameters, including albedo, amount of photosynthetically active vegetation and soil moisture, respectively. However, just as the interpretation of principal components is used as a descriptive tool rather than a precise measurement of biophysical phenomena, the tasselled cap indices do not directly measure albedo, amount of photosynthetically active vegetation or soil moisture. Though the indices have been used as a proxy for such direct measurements, the link is interpreted.

Since derivation of the tasselled cap relies on the rotation of principal components to be aligned with these interpreted features, the formulation process is not robust. Kauth and Thomas (1976) aligned the brightness axis with the 'major axis of soils'. Using Gram–Schmidt orthogonalization, greenness was defined orthogonally to brightness, and pointing to a 'green cluster' in the dataset identified visually. The yellowness and nonesuch features were defined similarly using Gram–Schmidt orthogonalization. Zhang *et al.* (2002) do not give an adequate description of the derivation of the rotation for MODIS, but imply its basis on discriminant functions of vegetated versus not vegetated, water and snow versus vegetated, and so on. Horne (2003) formulated a 'tasselled cap' transformation for IKONOS imagery, but chose not to rotate the principal components at all.

Due to the pluralistic interpretation of the tasselled cap features, no standards currently exist for deriving the rotation. With the choice of aligning parameter left to the researcher, any number of 'tasselled cap transformations' may be developed using any number of parameters. To avoid the multiplicity in transformation development introduced by the lack of standards in defining this largely descriptive tool, a more robust approach is presented here that provides a mechanism for maintaining continuity among sensors, thus retaining the meaning of the tasselled cap.

2. Objectives

The objective of this study was to develop a tasselled cap transformation for MODIS based on an independent derivation of principal component axes followed by a rotation of these axes to alignment with those of the TM tasselled cap. Global land cover patterns in the resulting feature space are also explored.

3. Transformation development

3.1 *Data*

MODIS Nadir BRDF Adjusted Reflectance Data (NBAR, MOD43B4) was used as input into the formulation process, rather than raw reflectance, because it standardizes reflectance to a nadir view, thus minimizing artifacts in the sample related to variable geometry (Schaaf *et al.* 2002). The NBAR spectral bands are comparable to those of Landsat TM, as summarized in table 1. Given the similarity of the two data structures confirmed by Zhang *et al.* (2002), NBAR was a logical choice for tasselled cap extension.

NBAR data quality varies. When sufficient high quality MODIS observations are available to adequately sample the BRDF, the Ross-Thick/Li-Sparse semi-empirical BRDF model is used to compute NBAR. Otherwise, a lower quality magnitude inversion is performed which couples *a-priori* knowledge of the surface anisotropy with any high quality MODIS observations that are available (Schaaf *et al.* 2002). Pixels computed using the primary model are identified by flags in the quality assurance (QA) dataset.

3.2 *Sampling*

The tasselled cap is based on principal components derived from a dataset that should represent the full range of variability of interest. Though these components are ultimately rotated, the 3D structure of the data space is retained through the rotation. The final transformation is thus highly contingent upon the chosen starting dataset.

An attempt was made to represent a wide variety of land cover types in the development of the TM tasselled cap (Crist 1983b, 1985, Crist and Cicone 1984a,b). Zhang *et al.* (2002) used 1300 sites representative of a range of conditions, each containing 25 1-km pixels.

For this study, a global extent of MODIS NBAR 16-day composites spanning 12 months from February 2000 to February 2001 was acquired from the EOS Data Gateway (http://edcimswww.cr.usgs.gov/pub/imswelcome/) for sampling. At first, only pixels with QA bits matching the first two rows in table 2 were considered, resulting in a cloud-free (but not snow-free) sample.

Since cloud cover can obscure large regions of the Earth for much of the year, a simple random sample would be heavily biased toward relatively cloud-free regions such as the Sahara Desert. A simple geographic stratification was used to ameliorate this problem: each of the 6550 1200 km × 1200 km tiles in the original dataset was split into 25 sections (each section is 240 km × 240 km). A mask was then created using the accompanying QA dataset to remove the snow, clouds and water. One

Table 1. Comparison of MODIS and Landsat Thematic Mapper (TM) spectral band widths.

	MODIS spectral band widths wavelength (nm)		TM spectral band widths wavelength (nm)	
	From	To	From	To
Red	620	670	630	690
NIR 1	841	876	760	900
Blue	459	479	450	520
Green	545	565	520	600
NIR 2	1230	1250	NA	NA
SWIR 1	1628	1652	1550	1750
SWIR 2	2105	2155	2080	2350

NIR, near infrared and SWIR, short-wavelength infrared.

Table 2. Summary of quality assurance (QA) bits used for masking the raw dataset to exclude unwanted pixels from the sample. A fuller description of QA bits is given at http://edcdaac.usgs.gov/modis/mod43b1.asp. The QA bits refer to level of processing based on assessed quality of reflectance, land cover type for each pixel and whether snow was present.

QA bits	Description	Usage
00–01	Mandatory QA	Processed, good quality pixels were extracted from the sample
04–07	Surface type	Only terrestrial pixels were sampled
16–17	Snow cover	Only pixels where snow cover was absent were sampled

tenth of one percent of the remaining pixels ($\sim 2.5 \times 10^6$) was randomly selected. Addition of this geographic stratification ensures that in a region of high cloud cover, any high quality pixels that are present are preferentially selected. This does not eliminate the bias, but does provide for a greater representation of cloud-obscured areas. It was desirable to use only the highest quality pixels in further analysis, thus all pixels with a mandatory QA flag of '00' to denote good quality in all bands were extracted ($\sim 1.2 \times 10^6$) to form the global sample.

3.3 *Sample evaluation*

For a gross estimate of how well the global sample represented the spectral characteristics of the full global dataset, the distribution of the global sample in spectral space was compared with that of the Earth. A histogram of the full 12-month population of spectral values of the Earth was calculated for each MODIS spectral band, including good quality pixels that were free of snow, water and clouds. Cumulative distribution functions (CDFs) built from these histograms were compared to those calculated from the global sample (figure 1). Points plotted in each figure form a very nearly one-to-one line, indicating a strong match between the sample and Earth CDFs. As the global histograms represent only good quality pixels, these CDF comparisons demonstrate only that the number of sample pixels is adequate; the geographic bias is not revealed here, and should be examined.

As expected, perpetually cloud-free areas such as the Saharan desert contribute more heavily to the sample than regions such as the tropics where cloud cover obscures large portions of the land surface for a significant portion of the year. The geographic range of the sample also changes over time as climatic patterns shift throughout the year (figure 2). To get an idea of the actual number of pixels drawn for the sample from different regions, four tiles having climatically disparate regimes were compared on numbers of sample pixels chosen over time (figure 3).

The temporal stability of the sample principal components was tested to assess how well the sample represented the range of global spectral variability through time. A significant lacking in representation of a major land cover condition in a given season would be expressed as a significant shift in the geometry of the sample principal component axes and thus their loadings values during that time period. The 12-month NBAR sample dataset included 23 sets of 16-day composites; the first three principal components of each of these 23 sets were derived and compared across time.

The temporal shifting in loadings corresponds directly to the changing geometry of the principal component axes in multispectral space. The first principal component was quite temporally dynamic, implying wide swings in the geometry

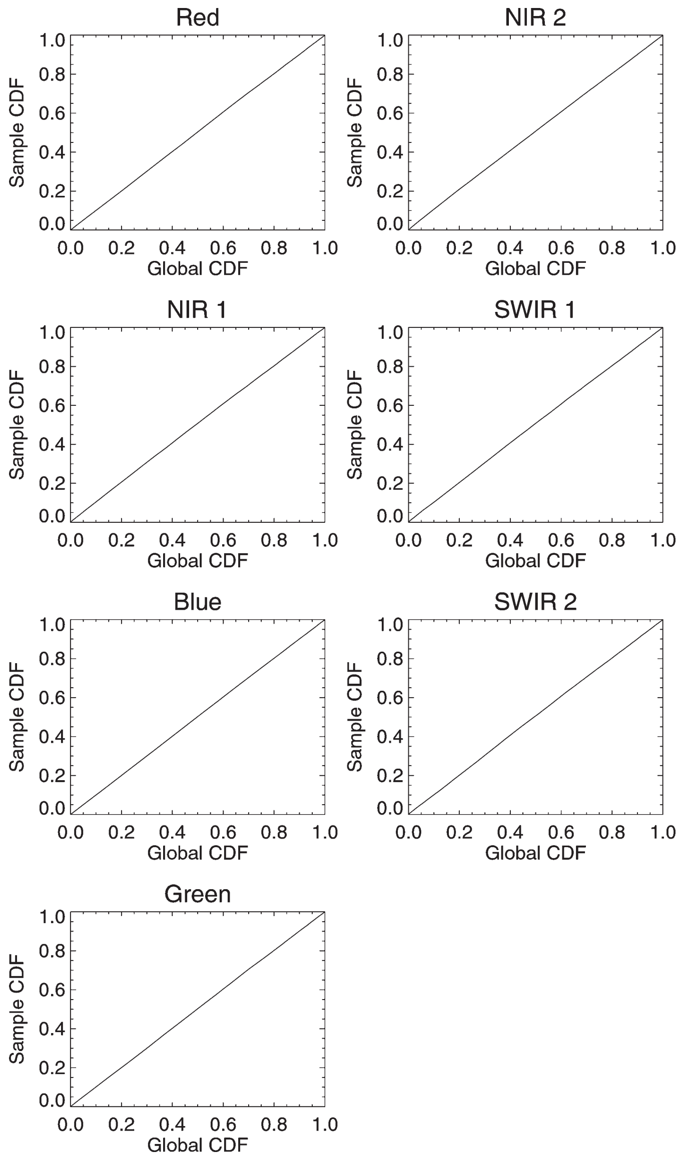


Figure 1. Sample cumulative distribution function (CDF) versus global CDF, for all seven raw Nadir BRDF-Adjusted Reflectance (NBAR) bands, as a demonstration of sample representativeness. NIR, near infrared and SWIR, short-wavelength infrared.

of this axis from one season to the next. Further exploration revealed that these extreme shifts were being caused by the shifting geographic extent of snow covered areas. At times when snow covered landscape had a large geographic extent, the sample variation was dominated by the snow versus no-snow signal. When the snow pack receded, the dominant signal became a weighted average of all bands, similar to conventional brightness (figure 4).

The principal component loadings were much more temporally stable when snow-covered pixels were removed from the sample (using QA bits 16–17, table 2), particularly the first principal component (figure 5) which accounts for over 90% of

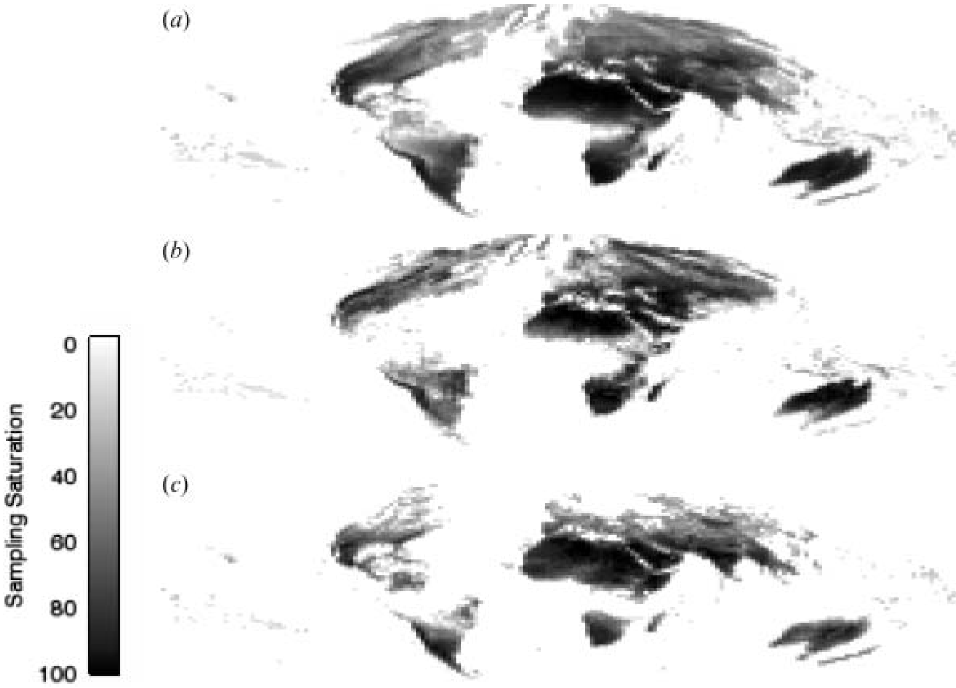


Figure 2. Temporal comparison of spatial density of global sample pixel locations: full year (*a*), 5 June through 28 August (*b*) and 1 January through 5 March (*c*). A 100% sampling saturation indicates the full 0.1% of pixels in the sampling block are represented in the sample.

the sample variance. The variation that remained may be attributed to temporally dynamic sampling; this variation, largely in the third component, was deemed relatively insignificant given the stable pattern of contrast among the spectral band weights. The temporal stability of the data structure implies stability of the tasselled cap features as well.

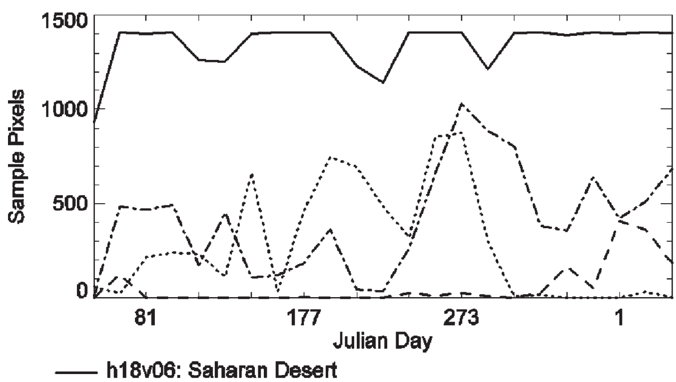


Figure 3. Counts over time of sample pixels from four MODIS tiles, chosen for their suspected contrast in temporal sample dynamics.

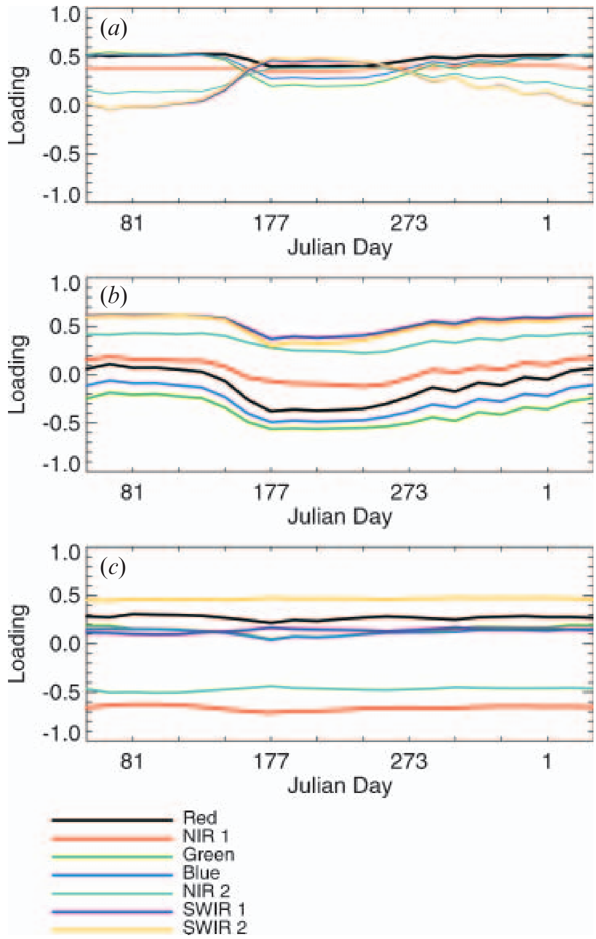


Figure 4. Temporal variation in loadings of principal component 1 (*a*), 2 (*b*), and 3 (*c*), of an initial random sample of pixels drawn from one year (beginning in February 2000) of global MODIS Nadir BRDF-Adjusted Reflectance (NBAR) 16-day composites. NIR, near infrared and SWIR, short-wavelength infrared.

3.4 *Principal components of the global sample*

As described earlier, the tasselled cap is a rigid rotation of principal components derived from a representative dataset. Thus, following an evaluation of the global sample described above, principal components were derived from the global sample. The characteristic tasselled cap features were apparent in the resulting sample principal component axis (PCA) space (figure 6). International Geosphere-Biosphere Programme (IGBP) land cover class information was acquired from the MODIS land cover product (MOD12Q1) from 2000 (Friedl *et al.* 2002) and added to the global sample data. IGBP classes were grouped into barren, cropland and forest groups and displayed as a set of three density plots in RGB (red, green, blue) colour space. Red, green and blue layers correspond to barren, cropland and forest subsets of the global sample. Cyan corresponds to areas in spectral space where the distributions of forests and croplands overlap. Yellow corresponds to areas where barren lands and croplands overlap.

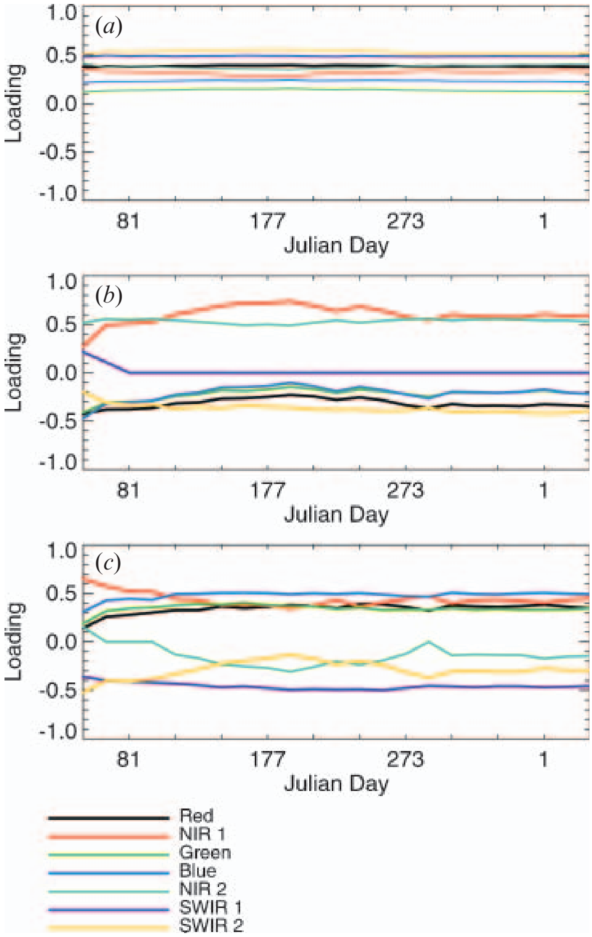


Figure 5. Temporal variation in principal component 1 (*a*), 2 (*b*) and 3 (*c*) of the global sample with the exclusion of snow. NIR, near infrared and SWIR, short-wavelength infrared.

The croplands group shows the characteristic tasselled cap shape first described by Kauth and Thomas (1976). The forestlands occupy a place named by Kauth and Thomas (1976) as the 'badge of trees'. Barren and sparsely vegetated areas occupied

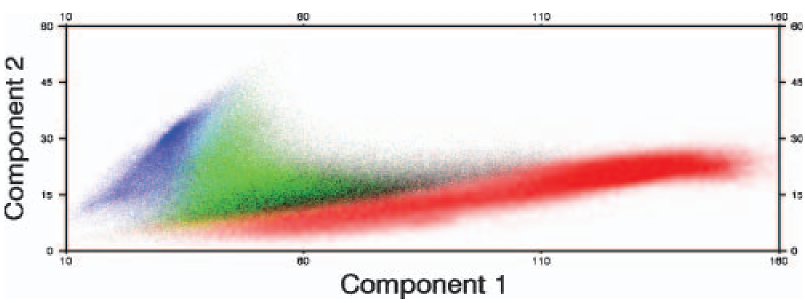


Figure 6. The global sample in principal component axes (PCA) space. Barren (red), croplands (green) and forest (blue) land cover groups are pictured as a set of layered density plots.

the region common to bare soil samples. All the major components of the TM tasselled cap space were visible in this MODIS PCA space; the only apparent difference was one of orientation.

3.5 *Rotation*

With a representative sample free of spurious influential outliers, PCA is a robust multivariate statistical tool (Joliffe 1986). In contrast, the process of rotation is subject to interpretation. As described in §1, the tasselled cap was derived as a descriptive tool, and the literature provides no standard set of parameters by which the principal components of a dataset may be rotated in alignment with tasselled cap features.

Crist and Cicone (1984a, p. 345) describe their rotation method for deriving a tasselled cap for simulated TM data in this way: 'These components were then rotated, two or three at a time, in a linear fashion which preserved the orthogonality of the six components. By the process of applying various rotations, the data relationships in the TM data space were discovered and defined.' The original TM tasselled cap space was thus defined through an exploratory, visual process. The derived coefficients were then applied directly to real TM data, and the resulting feature space plots revealed minor skews in data alignment that were corrected through visual interpretation (Crist and Cicone 1984c). Zhang *et al.* (2002) designed their MODIS tasselled cap to discriminate among a few basic landscape conditions, including vegetated, non-vegetated, and water and snow. The originally derived tasselled cap indices would discriminate among these landscape conditions, but this relationship is imprecise.

The absence of a robust rotation method presents the opportunity for any number of 'tasselled cap' transformations to be developed by rotating a PCA space to match empirical approximations of the biophysical parameters deemed most appropriate by the investigator. Even a slight alteration of the rotation modifies the geometry of the principal component axes and thus changes the meaning of the indices. Thus, until rotation standards are developed through a better understanding of the relationship between tasselled cap features and their corresponding biophysical parameters, the TM tasselled cap space that is so widely used and well established should be referenced when determining the proper orientation of a tasselled cap formulated for a new sensor.

Described below is a two-part process designed to align the MODIS PCA space with the TM tasselled cap space. Through this process, the data 'cloud' represented by the NBAR global sample transformed into PCA space is rotated to a least squares match with a pair-wise linked data cloud represented by the NBAR global sample transformed into TM tasselled cap space. The structure of the NBAR PCA space is retained, while the orientation of the TM tasselled cap is targeted.

The first step was to apply the TM tasselled cap coefficients to the NBAR global sample, creating a dummy target to which the NBAR PCA space would be aligned. The NBAR data was transformed into tasselled cap space using the TM tasselled cap equivalent transformation for reflectance factor data coefficients (Crist 1985), the best match for the atmospherically-corrected NBAR. The feature space was viewed (figure 7) to ensure that the dummy target had the proper orientation, a process described by Crist (1985) for extending the tasselled cap to other sources of reflectance data.

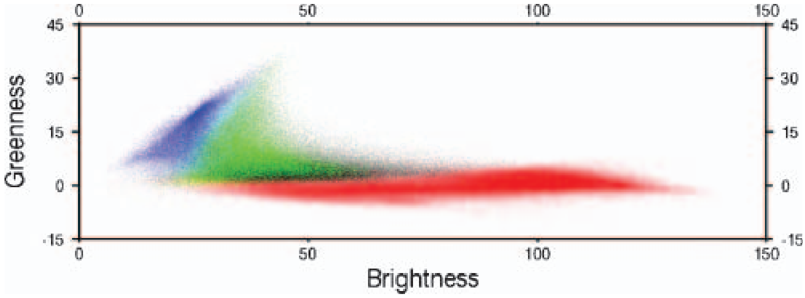


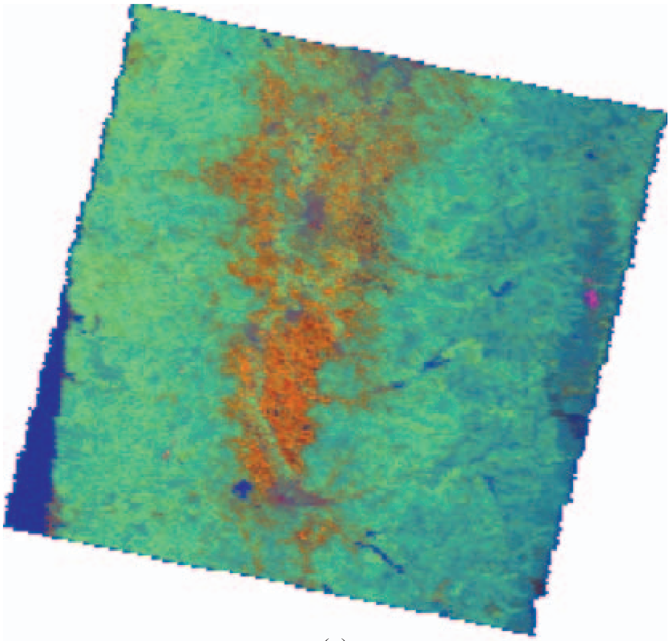
Figure 7. The global sample transformed using Landsat Thematic Mapper (TM) tasselled cap for reflectance coefficients. International Geosphere–Biosphere Programme (IGBP) class groupings are displayed as a set of three layered density plots in RGB space: barren in red, croplands in green and forests in blue colour.

Another step was taken to confirm the correspondence between TM tasselled cap transformed TM and NBAR data. Landsat scene path 46/row 29 from August 2000 was re-projected to the MODIS sinusoidal projection, atmospherically corrected and translated into reflectance using the 6S model (Vermote *et al.* 1997b), and spatially aggregated to 930 m to match the contemporaneous NBAR tile h09v04 in both projection and resolution (figure 8). These transformed TM and NBAR images are in UTM projection for greater interpretability, with NBAR clipped to the boundaries of the TM scene. The high correlations (0.97–0.99) and nearly one-to-one relationship between the NBAR and TM data, both transformed using TM tasselled, indicates the proper orientation of the NBAR sample in TM tasselled cap space (figure 9).

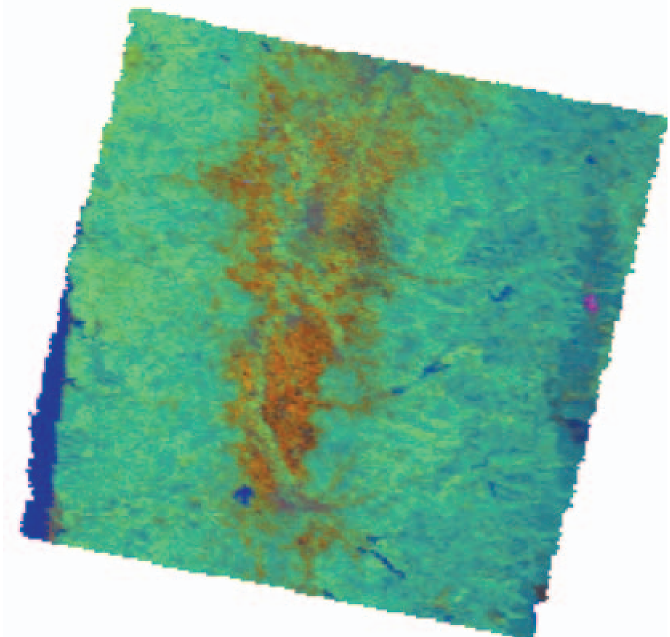
The second step uses a Procrustes rotation to align the NBAR PCA space with the dummy target. Procrustes, a common technique in multidimensional scaling, rotates a configuration of points to maximum similarity with a target configuration (Mardia *et al.* 1979). The rotation matrix derived using Procrustes is a least squares solution that was applied to the matrix of NBAR principal component loadings values in a simple matrix multiplication to generate a matrix of NBAR tasselled cap loadings.

Density plots of the global sample in the rotated NBAR PCA space reveal a structure and orientation comparable to the TM tasselled cap (figure 10), but another step was taken to confirm the correspondence. Landsat scene path 46/row 29, used in previous analysis, aggregated and re-projected to match its NBAR counterpart, was transformed into TM tasselled cap space and plotted against the corresponding NBAR data transformed into the Procrustes-rotated PCA space. Results showed a high correlation (figure 11).

MODIS tasselled cap coefficients are presented in table 3 and compared in figure 12 with TM tasselled cap coefficients and the coefficients derived by Zhang *et al.* (2002). The differences between the TM coefficients and the two sets of MODIS coefficients may be caused by the addition of MODIS band 5. This extra band would cause the band weights to be distributed somewhat differently for the MODIS bands, even when the proper data orientation is achieved. The differences between the two sets of MODIS coefficients are due to differences in methodology. The greatest differences appear to be in the wetness component. The original TM wetness index was referenced to soil moisture, whereas the Zhang *et al.* (2002) wetness was based on the discrimination between water and snow and vegetated



(*a*)



(*b*)

Figure 8. Comparison of Landsat Thematic Mapper (TM) scene path 46/row 29 from August 2000 and the contemporaneous MODIS tile (clipped), both transformed using TM tasselled cap coefficients (R/G/B, brightness/greenness/wetness, respectively). (*a*) TM scene path 46/row 29, atmospherically corrected and translated into reflectance using the 6S model, spatially aggregated to 930 m to closely match the spatial resolution of MODIS. (*b*) The corresponding clipped MODIS tile (h09 v04). Available in colour online.

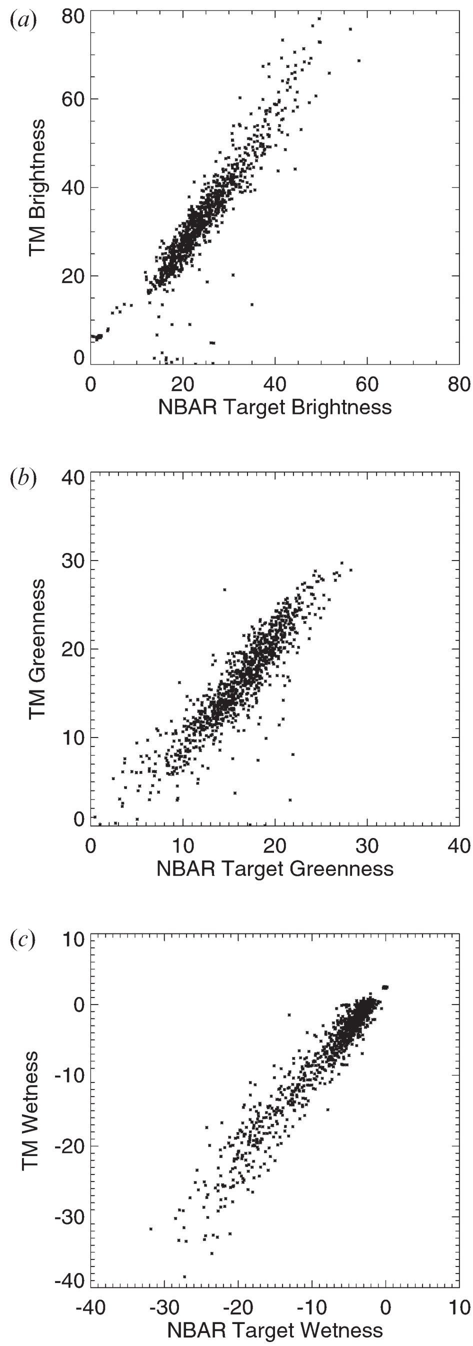


Figure 9. Pixel-to-pixel comparison of the paired images shown in figure 8, both transformed using Landsat Thematic Mapper (TM) tasselled cap coefficients. The three scatterplots displayed correspond to the three transformed band pairs (*a*) brightness (*b*) greenness (*c*) wetness. NBAR, Nadir BRDF-Adjusted Reflectance.

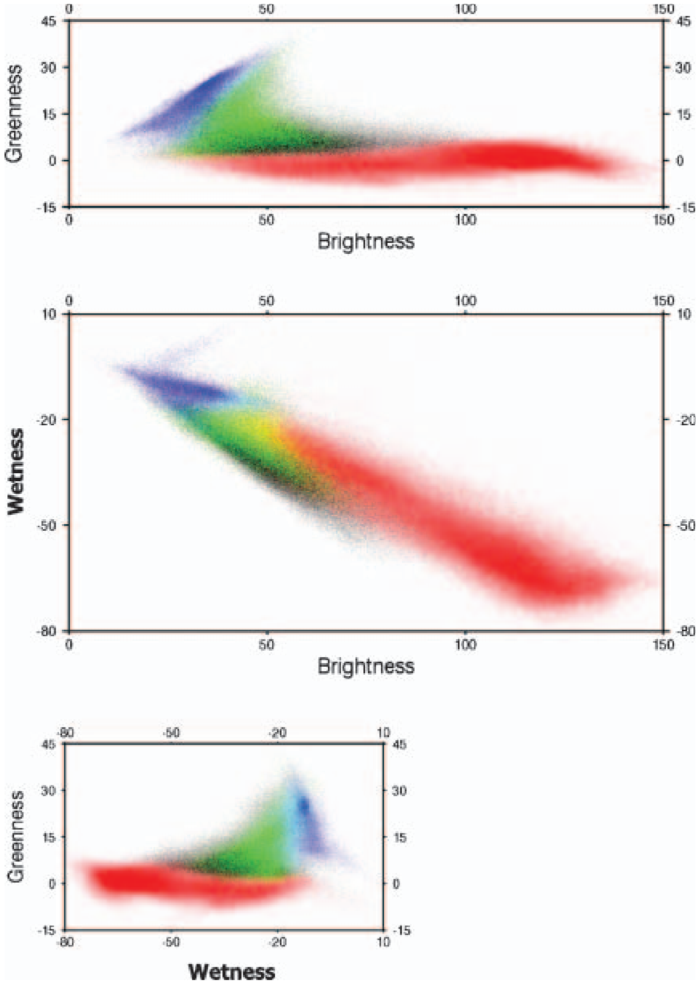


Figure 10. A global sample of MODIS Nadir BRDF-Adjusted Reflectance (NBAR) pixels in MODIS tasselled cap space. International Geosphere–Biosphere Programme (IGBP) land cover class groupings are displayed as a layered set of three density plots in RGB space: barren or sparsely vegetated areas in red, croplands in green and forests in blue colour. Areas in tasselled cap space where forests and croplands overlap are in cyan; overlap between barren and cropland regions are in yellow.

scene components. These differences highlight the multiplicity of interpretations of the tasselled cap features, particularly for wetness, and stress the importance of a standardized rotation procedure.

3.6 *Discussion of transformation development*

There are a number of sources of uncertainty potentially affecting the formulation of the MODIS tasselled cap. The formulation depends first and foremost on the distribution of sample pixels in spectral space, and this distribution may be slightly skewed by various artifacts in the original data. Topographic effects are not examined here, and atmospheric correction of the original data is somewhat variable across swath width. Native spatial resolution is also variable across swath width,

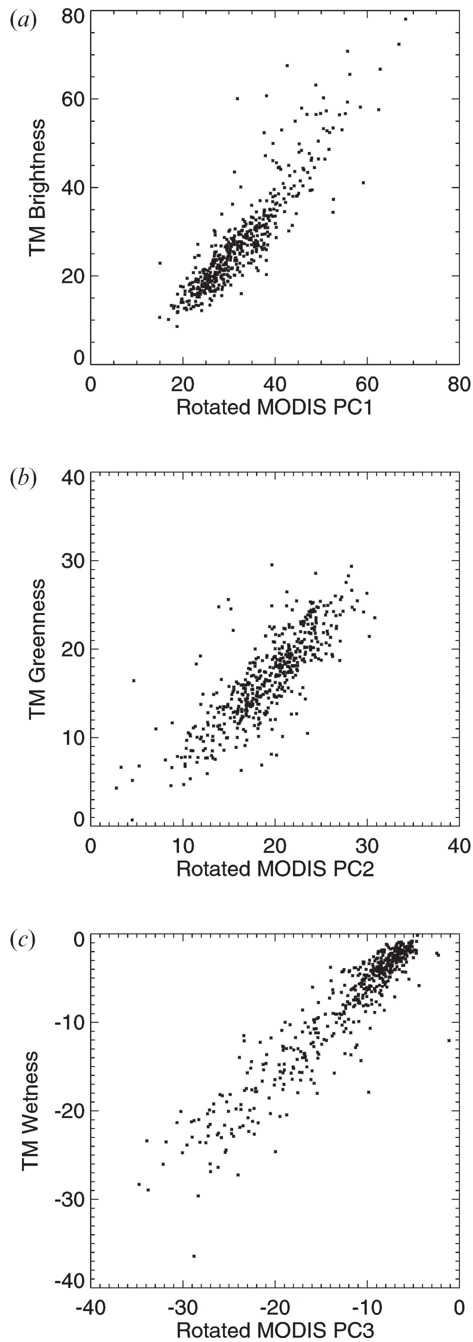


Figure 11. Pixel-to-pixel comparison of the paired images shown in figure 8, both transformed. The Landsat Thematic Mapper (TM) scene was transformed using the TM tasselled cap for reflectance coefficients. The MODIS image was transformed using the rotated principal component axes (PCA) loadings. The three scatterplots displayed correspond to the three transformed band pairs (*a*) brightness (*b*) greenness and (*c*) wetness.

Table 3. MODIS tasselled cap coefficients.

	Brightness	Greenness	Wetness
Red	0.4395	−0.4064	0.1147
NIR 1	0.5945	0.5129	0.2489
Blue	0.2460	−0.2744	0.2408
Green	0.3918	−0.2893	0.3132
NIR 2	0.3506	0.4882	−0.3122
SWIR 1	0.2136	−0.0036	−0.6416
SWIR 2	0.2678	−0.4169	−0.5087

NIR, near infrared and SWIR, short-wavelength infrared.

increasing up to fivefold in the off-nadir views (Vermote *et al.* 1997a). The objective of this study was to uncover major global sources of variation; it was assumed that these potential errors in the NBAR data were not significant enough to noticeably alter such broad patterns in vegetation dynamics, so their potential effects were not taken into consideration.

The rotation process presented here used a TM tasselled cap space as a standard to properly orient the NBAR tasselled cap because the TM tasselled cap is well established and widely used in the remote sensing community. It is recognized that in the future, a new standard may be developed based on a greater understanding of the relationship between the tasselled cap features and their corresponding biophysical parameters. The process used here may be used to maintain these standards across sensors, provided the same steps are taken:

1. Develop a sample representative of the full range of variability of interest.
2. Examine the PCA space to confirm the existence of tasselled cap features.
3. Create a dummy target through application of the TM tasselled cap coefficients directly to the dataset and confirm the proper orientation of tasselled cap features. This is only possible if the sensor in question has a close similarity with TM.

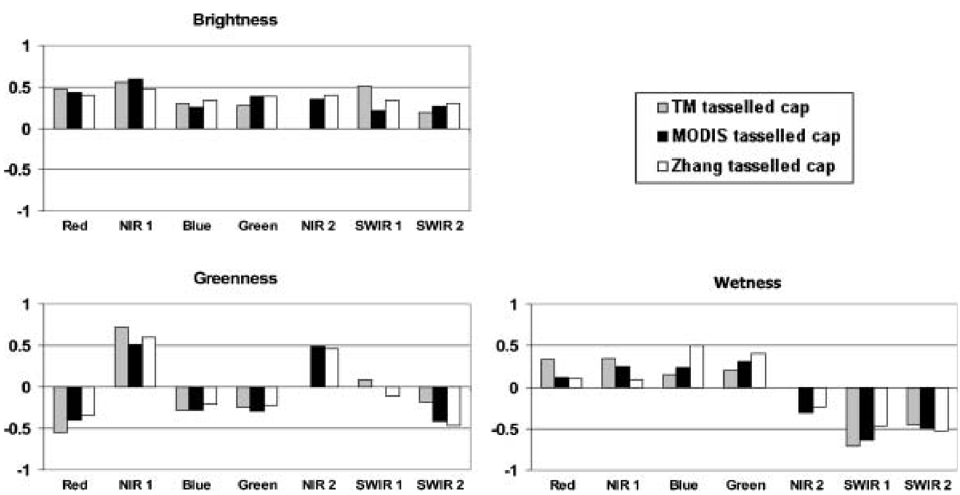


Figure 12. Comparison of MODIS tasselled cap coefficients with Landsat Thematic Mapper (TM) tasselled cap coefficients and coefficients derived by Zhang *et al.* (2002). NIR, near infrared and SWIR, short-wavelength infrared.

4. Use a Procrustes rotation to rotate the PCA-transformed sample to the best alignment with the dummy target.

Using this approach to tasselled cap derivation, future studies utilizing multiple types of imagery may be better facilitated by the development of indices that are directly comparable to their TM counterparts. With the continual design and launch of new sensors, it becomes important to maintain continuity among them.

The discovery of a MODIS tasselled cap has implications beyond the resulting set of coefficients presented here. The data source and sampling strategy used here represent a significant departure from the TM tasselled cap development process; that a tasselled cap occurs naturally in the global, multi-temporal MODIS data space implies a scalability of the tasselled cap concept in both time and space. It seems the tasselled cap is an intrinsic property of terrestrial reflectance at multiple scales and across time.

4. Feature space exploration

The tasselled cap transformation originally got its name from the shape of crop spectral development trajectories through the growing season. Kauth and Thomas (1976) first identified this pattern in feature space; Crist (1983b) further developed the concept with the addition of the wetness index. A plot of bare soil before planting would be viewed best in the plane of soils (brightness/wetness space), then would shift up through the transition zone (greenness/wetness space) toward the plane of vegetation (brightness/greenness space) as the crops matured, then would 'tassel out' with senescence. A group of such plots, all starting with different soil conditions, would together form the shape of a 'tasselled woolen cap'.

The form of this distribution is identifiable in both the TM tasselled cap and the MODIS tasselled cap spaces. There are other land cover-related features visible in the TM tasselled cap space, such as regions associated with water, human-made materials and forest (Crist 1983b). The NBAR MODIS tasselled cap space offers the same interpretability and analysis of an annual dataset representative of the entire globe offers a more sophisticated, better integrated view of the temporal spectral properties of global vegetation characteristics. In the following set of analyses, this global sample was linked to other global products and displayed in MODIS tasselled cap space, giving a simple graphical representation of global vegetation characteristics.

4.1 *Land cover analysis*

Plotting the global sample in feature space in terms of IGBP land cover classes (table 4) as described earlier is one way to demonstrate how the characteristics of global vegetation can be interpreted using tasselled cap indices.

Three distinct clusters are apparent in tasselled cap feature space (figure 10), and each is related to a different group of IGBP classes shown here as a set of three layered density plots in RGB space—barren in red, croplands in green and forest in blue. Areas in spectral space where barren and cropland distributions overlap are in yellow and overlap between forest and croplands is cyan. Barren or sparsely vegetated areas have the broadest distribution in brightness and wetness, owing to the vast amount of diversity in physical condition of these areas, which include moist and dry soil, bare rock, lava and sand. Croplands have the next highest amount of spectral diversity in all three indices, and forest classes occupy a relatively

Table 4. International Geosphere–Biosphere Programme (IGBP) land cover units.

IGBP land cover units (Strahler *et al.* 1999)	
Evergreen needleleaf forests	Lands dominated by woody vegetation with a percent cover >60% and height exceeding 2 m. Almost all trees remain green all year. Canopy is never without green foliage
Evergreen broadleaf forests	Lands dominated by woody vegetation with a percent cover >60% and height exceeding 2 m. Almost all trees and shrubs remain green all year round. Canopy is never without green foliage
Deciduous needleleaf forests	Lands dominated by woody vegetation with a percent cover >60% and height exceeding 2 m. Consists of seasonal needleleaf tree communities with an annual cycle of leaf-on and leaf-off periods
Deciduous broadleaf forests	Lands dominated by woody vegetation with a percent cover >60% and height exceeding 2 m. Consists of broadleaf tree communities with an annual cycle of leaf-on and leaf-off periods
Mixed forests	Lands dominated by trees with a percent cover >60% and height exceeding 2 m. Consists of three communities with interspersed mixtures or mosaics of the other four forest types. None of the forest types exceed 60% of the landscape
Closed shrublands	Lands with woody vegetation less than 2 m tall and with shrub canopy cover >60%. The shrub foliage can be either evergreen or deciduous
Open shrublands	Lands with woody vegetation less than 2 m tall and with shrub canopy cover between 10–60%. The shrub foliage can be either evergreen or deciduous
Woody savannas	Lands with herbaceous and other understory systems, and with forest canopy cover between 30–60%. The forest cover height exceeds 2 m
Savannas	Lands with herbaceous and other understory systems, and with forest canopy cover between 10–30%. The forest cover height exceeds 2 m
Grasslands	Lands with herbaceous types of cover. Tree and shrub cover is less than 10%
Permanent wetlands	Lands with a permanent mixture of water and herbaceous or woody vegetation. The vegetation can be present in either salt, brackish or fresh water
Croplands	Lands covered with temporary crops followed by harvest and a bare soil period (e.g. single and multiple cropping systems). Note that perennial woody crops are classified as the appropriate forest or shrub land cover type
Urban and built-up lands	Land covered by buildings and other man-made structures
Cropland/natural vegetation mosaics	Lands with a mosaic of croplands, forests, shrubland and grasslands in which no one component comprises fore than 60% of the landscape
Snow and ice	Lands under snow/ice cover throughout the year
Barren	Lands with exposed soil, sand, rocks or snow and never has more than 10% vegetated cover during any time of the year
Water bodies	Oceans, seas, lakes, reservoirs and rivers. Can be either fresh or salt-water bodies

smaller region in tasselled cap space. Although forests are generally more structurally diverse than crops and the forest group includes types that undergo significant phenological changes over the course of the year, in spectral terms their distribution is relatively more constrained. This is due most likely to the greater range of vegetation condition that falls into the croplands group. Areas called 'cropland' under the IGBP classification undergo a number of different stages of growth and senescence throughout the year, so these sample pixels represent a considerable array of phenological conditions, including bare soil, growing and mature vegetation and senescent vegetation.

Though more obvious when comparing broad land cover groups, different forest classes within the broad forest group described above may also be distinguished by their varying spectral ranges (figure 13). Evergreen broadleaf forest occupies a slightly different region in spectral space than evergreen needleleaf forest, which is darker and less green. Deciduous broadleaf forest and deciduous needleleaf forest show two markedly different distributions in tasselled cap space, relating to their

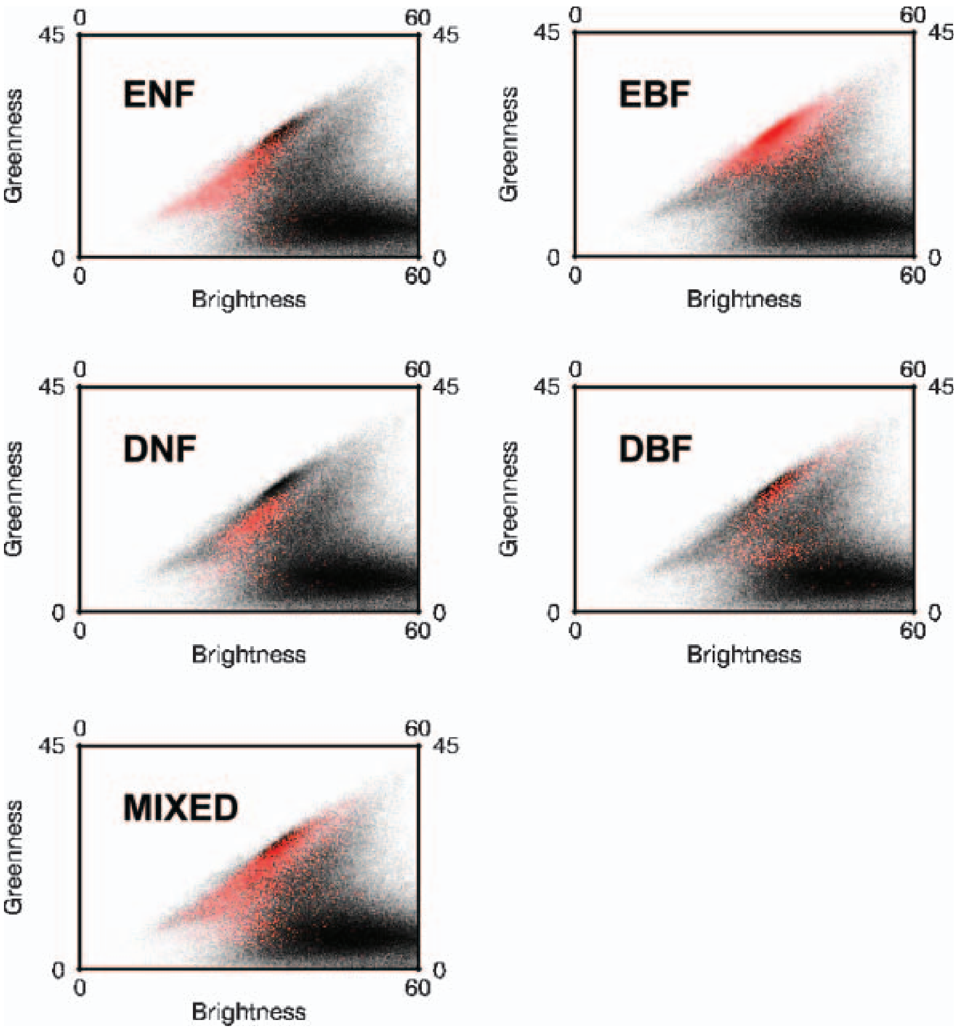


Figure 13. The five International Geosphere–Biosphere Programme (IGBP) forest classes in tasselled cap space: evergreen needleleaf forest (ENF), evergreen broadleaf forest (EBF), deciduous needleleaf forest (DNF), deciduous broadleaf forest (DBF) and mixed forest. Forest class distributions are displayed as density plots in red overlaid on global sample density plots in black.

two very different phenological conditions. The leaf-on condition in each case is significantly greener than the leaf-off condition. This phenological signal is confirmed in the next section. Mixed forests span most of the region occupied by forest classes, owing to its compositional, structural and phenological diversity.

This simple graphical display aids considerably in understanding the general layout of global land cover classes in spectral space, including their boundaries and the nature of their intersections. The same kind of visual analysis would be useful in understanding temporal dynamics as well, but subtle phenological changes would get lost using such a broad dataset. It is more useful to focus in on smaller scale plots where land cover is known.

4.2 *BigFoot data analysis of land cover*

The BigFoot Project sites were used to explore phenological characteristics of several different biomes (Cohen *et al.* 2006). The BigFoot project was designed to validate certain MODIS products by linking remote sensing data with *in situ* measurements. Nine sites were chosen to represent the different biomes of the Earth, and land cover is just one of the biophysical variables known in detail for the spatial extent of each site. Eight sites in the Northern Hemisphere were used here in analysis (see table 5 for a summary).

The spectral properties of BigFoot sites in relation to the Earth as a whole can be made clear in a simple display (figure 14). Here, plots of the Northern Hemisphere summer (25 June through 28 August) and winter (1 January through 5 March) MODIS tasselled cap values for BigFoot sites were overlaid on density plots of the global sample, displayed in both brightness–greenness space (plane of vegetation) and brightness–wetness space (plane of soils). Certain sites, such as TUND, have no data points for the winter months, when the land is covered in snow and pixels were filtered out using NBAR QA flags. However, the other sites express the phenological differences between summer and winter months in the spectral differences shown in tasselled cap space. AGRO, an Illinois agricultural site, has apparent spectral differences between the growing and dormant stages. This basic temporal trend ties together all the BigFoot sites with apparent seasonal changes. In the summer, most sites will migrate to brighter and greener regions in spectral space then return to their original locations in the winter.

One interesting artifact to note is the spur at the uppermost tip of the distribution, as seen in the plane of soils. Its placement is unusual: it is a significant departure from the regular forest spectral distribution, yet, both METL, a temperate, dry, open-canopy forest site, and HARV, a deciduous broadleaf site, occupy this region

Table 5. Summary of the eight BigFoot sites used in this analysis. All sites are within the United States, except where noted.

AGRO	Agricultural site in Illinois
CHEQ	Mixed forest site in Wisconsin
HARV	Harvard Forest—deciduous broadleaf forest in Massachusetts with some evergreen needleleaf forest
KONZ	Konza Prairie—tallgrass prairie site in Kansas
METL	Evergreen needleleaf forest site in Oregon
NOBS	Boreal forest site (evergreen needleleaf) in Manitoba, Canada
SEVI	Desert site in Arizona
TUND	Arctic tundra site in Barrow, Alaska

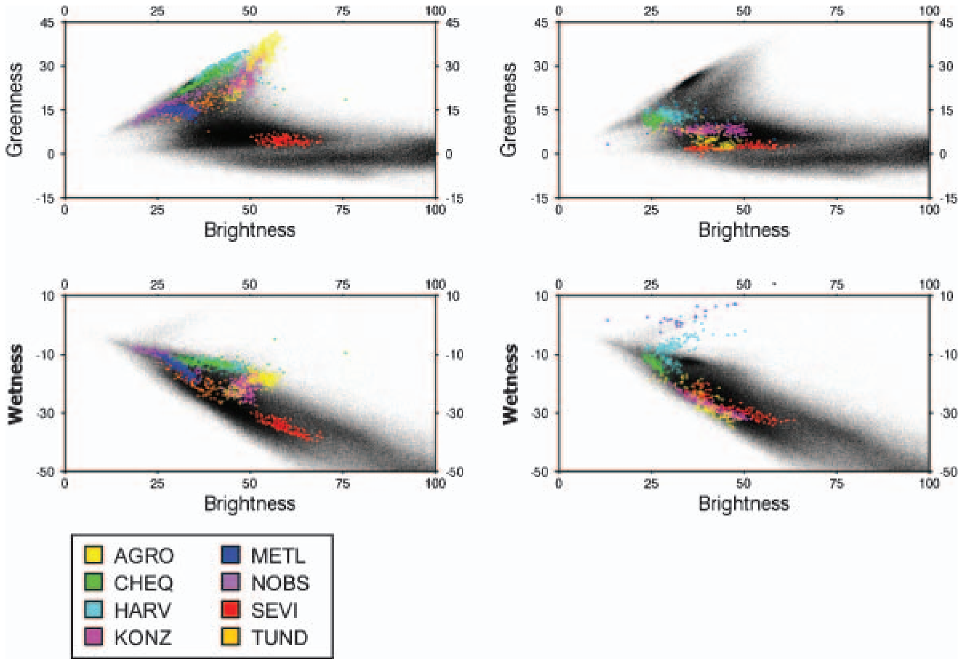


Figure 14. Eight BigFoot sites representing eight different biomes plotted in tasselled cap space, overlaid on the global sample density plot (in black). Two views of the tasselled cap space are presented here, both in northern hemisphere summer (25 June to 31 August) on the left and winter (1 January to 5 March) on the right. The brightness–wetness view (plane of soils) is shown to highlight the spur of BigFoot data that extends beyond the apparent boundaries of the global sample distribution in the winter months.

in the winter. It is likely that this spur is the spectral expression of a forest canopy with some amount of snow underneath. Though pixels containing snow were eliminated from the plot using the QA flags, the algorithm used to determine whether a pixel contains snow has an unknown threshold (Hall *et al.* 2002). A pixel with snow beneath a forest canopy may fall under this threshold and not get flagged.

4.3 *Vegetation continuous fields*

A clear distinction between the spectral ranges of forest, cropland and barren land cover groups has been shown in the previous analyses. So far, each pixel has been

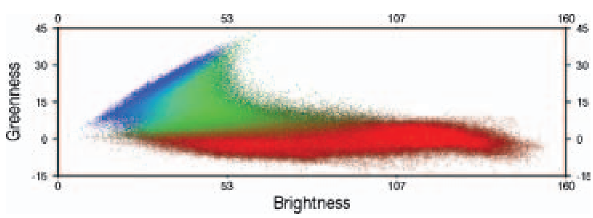


Figure 15. The MODIS Vegetation Continuous Fields (VCF) product in tasselled cap space presented as a set of three layered percent value maps. Regions in feature space with the highest red value correspond to global sample points that have the highest percentage of barren cover. Similarly, green corresponds to herbaceous cover and blue corresponds to tree cover. Boundary areas, where the percent value maps overlap, represent global sample points that have a mixture of cover types.

considered to belong to a single land cover class. However, 1-km pixels generally represent a mixture of land cover classes, and it is valuable to understand how the percent cover of pixels of a given class influences its spectral range. The MODIS Vegetation Continuous Fields (VCF) product (MOD44) (Hansen *et al.* 2003) was used to begin to explore this question. Though data describing each MODIS pixel as a percentage of each of the IGBP land cover classes is not available, the VCF product does describe each pixel as a mixture of barren, herbaceous and woody cover types. Linking the VCF product to the global sample enabled the visualization of each pixel as a mixture of these three cover types.

The VCF is a 500 m product as opposed to the 1-km NBAR, so the percentage values were added to the global sample by taking the mean of the four pixels associated with each global sample pixel. Feature space plots (figure 15) of each of these land cover types, varying in colour by percent cover, correspond as expected with the land cover plots shown previously. Percent tree cover is highest in the same spectral region where forest classes are found, croplands match up with areas of higher percentage herbaceous cover and bare soil areas match up with areas of low or no vegetation cover.

In each of these three land cover groupings, percent cover is highest toward the centre of the distribution and decreases toward the edges. These edges are thought to correspond to mixed pixels. There is a convincing gradient, for example, between the herbaceous and tree cover types: moving in a direction from herbaceous to woody cover in spectral space corresponds to a steady decrease in herbaceous cover and a steady increase in woody cover. This suggests that use of the MODIS tasselled cap space as a linear mixing space, relevant to the global scale, could be investigated.

5. Conclusions

Working with a global sample of data is useful and enlightening and presents opportunities for uncovering and understanding the properties of global land cover characteristics. Though general patterns of land cover in tasselled cap space have been known for decades, generalizing these patterns to the global scale through graphical analysis of a globally representative dataset has never before been attempted. Such a knowledge base provides a global context for future work at both the global and regional level.

An exploration of the global sample in MODIS tasselled cap space yielded identification of land cover patterns that agreed with earlier feature space demonstrations (e.g. Crist and Cicone 1984a,b). The major difference is the breadth and scope of analysis. The MODIS tasselled cap has great potential for application in temporal analysis and interpretation of land cover characteristics. It may be more desirable to use a single vegetation index in some cases; brightness, greenness and wetness are useful as stand-alone indices. However, the real power of the MODIS tasselled cap may be found in the conjunction of all three. The 3D tasselled cap space provides a unique context for interpretation and exploration of MODIS data. The utility and relevance of the MODIS tasselled cap transformation has only begun to be explored here; further work will likely expand the role of the tasselled cap in land cover studies.

Although this study was designed to explore global land cover trends by taking advantage of available global MODIS products, an unexpected but relevant additional outcome was the observed relationship among these products in tasselled cap space. Examining the behaviour of multiple global products in a space designed to maximize global spectral variance seems a simple, effective means to their cross-validation.

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References

COHEN, W.B., MAIERSPERGER, T.K., TURNER, D.P., RITTS, W.D., PFLUGMACHER, D., KENNEDY, R.E., KIRSCHBAUM, A., RUNNING, S.W., COSTA, M. and GOWER, S.T., 2006, MODIS land cover and LAI Collection 4 product quality across nine sites in the Western Hemisphere. *IEEE Transactions on Geoscience and Remote Sensing*, **44**, pp. 1843–1857.

COHEN, W.B. and SPIES, T.A., 1992, Estimating structural attributes of Douglas-fir/western hemlock forest stands from Landsat and SPOT imagery. *Remote Sensing of Environment*, **41**, pp. 1–17.

COHEN, W.B., SPIES, T.A. and FIORELLA, M., 1995, Estimating the age and structure of forests in a multi-ownership landscape of western Oregon, USA. *International Journal of Remote Sensing*, **16**, pp. 721–746.

CRIST, E.P., 1983a, Cultural and environmental effects on crop spectral development patterns as viewed by Landsat. In *Proceedings of the Seventeenth International Symposium on Remote Sensing of Environment*, Ann Arbor, MI, 9–13 May, **1**, pp. 433–442 (Ann Arbor, MI: Environmental Research Institute of Michigan).

CRIST, E.P., 1983b, The Thematic Mapper tasseled cap—a preliminary formulation. Machine processing of remotely sensed data: Natural resources evaluation. In *Proceedings of the Ninth International Symposium*, Purdue University, West Lafayette, IN, 21–23 June, pp. 357–364.

CRIST, E.P., 1985, A TM tasseled cap equivalent transformation for reflectance factor data. *Remote Sensing of Environment*, **17**, pp. 301–306.

CRIST, E.P. and CICONE, R.C., 1984a, Application of the tasseled cap concept to simulated Thematic Mapper data. *Photogrammetric Engineering and Remote Sensing*, **50**, pp. 343–352.

CRIST, E.P. and CICONE, R.C., 1984b, A physically-based transformation of Thematic Mapper data—the TM tasseled cap. *IEEE Transactions on Geoscience and Remote Sensing*, GE-**22**, pp. 256–263.

CRIST, E.P. and CICONE, R.C., 1984c, Comparisons of the dimensionality and features of simulated Landsat-4 MSS and TM data. *Remote Sensing of Environment*, **14**, pp. 235–246.

CRIST, E.P., LAURIN, R. and CICONE, R.C., 1986, Vegetation and soils information contained in transformed Thematic Mapper data. In *Proceedings of IGARSS '86 Symposium*, edited by, Zurich, Switzerland, 8–11 September (Paris: European Space Agency Publications Division), pp. 1465–1470.

DYMOND, C.C., MLADENOFF, D.J. and RADELOFF, V.C., 2002, Phenological differences in tasseled cap indices improve deciduous forest classification. *Remote Sensing of Environment*, **80**, pp. 460–472.

FRIEDL, M.A., MCIVER, D.K., HODGES, J.F.C., ZHANG, X.Y., MUCHONEY, D., STRAHLER, A.H., WOODCOCK, C.E., GOPAL, S., SCHNEIDER, A., COOPER, A., BACCINI, A., GAO, F. and SCHAAF, C., 2002, Global land cover mapping from MODIS: algorithms and early results. *Remote Sensing of Environment*, **83**, pp. 287–302.

HALL, D.K., RIOGS, G.A., SALOMONSON, V.V., DIGIROLAMO, N. and BAYR, K.J., 2002, MODIS snow-cover products. *Remote Sensing of Environment*, **83**, pp. 181–194.

HANSEN, M.C., DEFRIES, R.S., TOWNSHEND, J.R.G., CARROLL, M., DIMICELI, C. and SOHLBERG, R.A., 2003, Global percent tree cover at a spatial resolution of 500 meters: first results of the MODIS Vegetation Continuous Fields Algorithm. *Earth Interactions*, **1**, pp. 7.

HORNE, J.H., 2003, A tasseled cap transformation for IKONOS images. *ASPRS Annual Conference Proceedings*, Anchorage, Alaska, 3–9 May (Bethesda, MD: American Society of Photogrammetry and Remote Sensing), pp. 1–7.

JOLIFFE, I.T., 1986, *Principal Component Analysis* (New York: Springer-Verlag).

KAUTH, R.J. and THOMAS, G.S., 1976, The tasseled cap—a graphic description of the spectral temporal development of agricultural crops as seen by Landsat. In *Proceedings of the Symposium on Machine Processing of Remotely Sensed Data*, Purdue University, W. Lafayette, IN, 29 June – 1 July 4B41–4B51.

MARDIA, K.V., KENT, J.T. and BIBBY, J.M., 1979, *Multivariate Analysis* (London: Academic Press).

OETTER, D.R., COHEN, W.B., BERTERRETCHE, M., MAIERSPERGER, T.K. and KENNEDY, R.E., 2001, Land cover mapping in an agricultural setting using multiseasonal Thematic Mapper data. *Remote Sensing of Environment*, **72**, pp. 139–155.

SCHAAF, C.B., GAO, F., STRAHLER, A.H., LUCHT, W., LI, X., TSANG, T., STRUGNELL, N.C., ZHANG, X., JIN, Y., MULLER, J., LEWIS, P., BAMSLEY, M., HOBSON, P., DISNEY, M., ROBERTS, G., DUNDERDALE, M., DOLL, C., D'ENTREMONT, R.P., HU, B., LIANG, S., PRIVETTE, J.L. and ROY, D., 2002, First Operational BRDF, albedo and nadir reflectance products from MODIS. *Remote Sensing of Environment*, **83**, pp. 135–148.

SKAKUN, R.S., WULDER, M.A. and FRANKLIN, S.E., 2003, Sensitivity of the thematic mapper enhanced wetness difference index to detect mountain pine beetle red-attack damage. *Remote Sensing of Environment*, **86**, pp. 433–443.

STRAHLER, A., MUCHONEY, D., BORAK, J., FRIEDL, M., GOPAL, S., LAMBIN, E. and MOODY, A., 1999, MODIS Land Cover and Land-Cover Product Algorithm Theoretical Basis Document (ATBD) Version 5.0. Boston, MA: Center for Remote Sensing, Boston University, http://modis.gsfc.nasa.gov/data/atbd/atbd_mod12.pdf, 72 pp.

TODD, S.W., HOFFER, R.M. and MILCHUNAS, D.G., 1998, Biomass estimation on grazed and ungrazed rangelands using spectral indices. *International Journal of Remote Sensing*, **19**, pp. 427–438.

VERMOTE, E.F., EL SALEOUS, N.Z., JUSTICE, C.O., KAUFMAN, Y.J., PRIVETTE, J., REMER, L.C. and TANRE, D., 1997a, Atmospheric correction of visible to middle infrared EOS-MODIS data over land surface, background, operational algorithm and validation. *Journal of Geophysical Research*, **102**, pp. 17–131.

VERMOTE, E.F., TANRE, D., DEUZE, J.L., HERMAN, M. and MORCRETTE, J.J., 1997b, Second simulation of the satellite signal in the solar system, 6S: an overview. *IEEE Transactions on Geoscience and Remote Sensing*, **35**, pp. 675–686.

ZHANG, X.Y., SCHAAF, C.B., FRIEDL, M.A., STRAHLER, A.H., GAO, F. and HODGES, J.F.C., 2002, MODIS tasseled cap transformation and its utility. In *Proceedings of the International Geoscience and Remote Sensing Symposium (IGARSS '02)*, edited by, Toronto, Canada, 24–28 June (Piscataway, NJ: IEEE), pp. 1063–1065.