ARTICLE IN PRESS

ISPRS Journal of Photogrammetry and Remote Sensing xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

Bidirectional effects in Landsat reflectance estimates: Is there a problem to solve?

Jyoteshwar R. Nagol [a,*], Joseph O. Sexton [a], Do-Hyung Kim [a], Anupam Anand [a], Douglas Morton [b], Eric Vermote [b], John R. Townshend [a]

[a] *Global Land Cover Facility, Department of Geographical Sciences, University of Maryland, College Park, MD, USA*
[b] *Biospheric Sciences Branch, NASA Goddard Spaceflight Center, Greenbelt, MD, USA*

ARTICLE INFO

Article history:
Received 1 July 2013
Received in revised form 28 February 2014
Accepted 11 September 2014
Available online xxxx

Keywords:
Landsat
BRDF
Phenology
NDVI
EVI
MODIS
Absolute correction

ABSTRACT

Since the 2008 opening of the USGS Landsat archive, research has focused on standardization and compositing of dense time series of Landsat images to increase measurement precision sufficiently for long-term and/or global land cover mapping. Most of these efforts rely on atmospherically corrected estimates of surface reflectance, some of which also incorporate corrections for effects of sun-target-sensor geometry. However, these effects have not yet been well-characterized in Landsat data. Using reflectance and Bidirectional Reflectance Distribution Function (BRDF) parameters derived from daily Moderate-resolution Imaging Spectroradiometer (MODIS) reflectance estimates and the sun-target-sensor geometry of the Landsat-5 orbit, we simulated the BRDF effects within the Landsat-5 data archive at three sites representing low, mid, and high latitudes. We found that bidirectional effects are prevalent in Landsat measurements, but their effect varies by latitude. Seasonal variations in illumination geometry affect reflectance as well as vegetation indices, adding spurious seasonality in otherwise stable evergreen phenology at a lower-latitude tropical forest site. The ±7.5° variation in View Zenith Angle (VZA), usually considered negligible, resulted in as much as 20% along-scan variation in reflectance at the lower latitude site. Although variation in Solar Zenith Angle (SZA) is less pronounced in the tropics than in the upper latitudes, its impact is most significant in the tropics due to the relative proximity of Landsat scans to the principle plane. For this reason, even small variations in viewing and illumination geometry have large impacts on reflectance and vegetation indices near the equator. In contrast, the amplitude of SZA and phenological variations have the greatest impact on reflectance estimates in mid-and upper latitudes, where interaction between phenological variation and Landsat's 16-day orbital cycle can be greater than the combined effect of BRDF and orbital drift. Our analysis suggests that accounting or correction for BRDF effects will increase precision of land cover mapping and monitoring based on Landsat data alone or in combination with other sensors.

1. Introduction

The Landsat series of satellites has collected radiometric measurements of Earth's terrestrial and near-shore surface since 1972, providing an unparalleled record of the status and dynamics of Earth's ecosystems and human activity (Cohen and Goward, 2004). Since 2008, all new and archived Landsat images held by the United States Geological Survey (USGS) have been made freely available to any user (Woodcock et al., 2008; Wulder et al., 2012). This availability of dense, long-term time series of images covering the globe has led to numerous approaches to mapping and monitoring land cover, many of which rely on the consistency of physically based estimates of surface reflectance (Townshend et al., 2012; Giri et al., 2013).

Atmospherically corrected estimates of surface reflectance have led to improved quality of Landsat-based land-cover maps at regional and global scales (Kennedy et al., 2009; Sexton et al., 2013a,b), but continued improvement requires further understanding of the sources of variation in radiometric measurements. A range of spatio-temporal variables influence optical measurements, including atmospheric, phenological, and moisture conditions (Schott et al., 1988; Hall et al., 1991; Yuan and Elvidge, 1996). Impacts from changes in the atmosphere and land surface on Landsat

---

* Corresponding author.
E-mail address: jnagol@umd.edu (J.R. Nagol).

http://dx.doi.org/10.1016/j.isprsjprs.2014.09.006
0924-2716/

Please cite this article in press as: Nagol, J.R., et al. Bidirectional effects in Landsat reflectance estimates: Is there a problem to solve? ISPRS J. Photogram. Remote Sensing (2014), http://dx.doi.org/10.1016/j.isprsjprs.2014.09.006

observations are widely recognized in the remote sensing community. However, impacts of sun-target-sensor geometry are rarely considered in Landsat data, even though Bidirectional Reflectance Distribution Function (BRDF) effects are well characterized in coarser-resolution datasets such as the Moderate-resolution Imaging Spectrometer (MODIS).

BRDF describes the variation of surface reflectance with changing illumination and viewing geometry – i.e., Solar Zenith Angle (SZA), View Zenith Angle (VZA), and Relative Azimuth Angle (RELAZ) (Fig. 1). Although most models of surface reflectance currently assume that land cover reflects equally in all directions, changes in the amount of shadow cast within the reflecting medium (e.g., vegetation) and the proportion of shadows visible to the sensor cause variation in directional reflectance. Further multiple scattering also contributes to directional variations in reflectance. The magnitude of BRDF-induced variations in reflectance estimates are most prominent along the direction of illumination, or "principle plane", where RELAZ = 0° or 180°.

Early studies noted the effect of BRDF on estimates of surface reflectance, vegetation indices, and land cover classification. Duggin (1977) noted the importance of "anniversary" image acquisition in studies of seasonal changes in green biomass. Middleton (1991) found that surface reflectance and the Normalized Difference Vegetation Index (NDVI) were affected by SZA in prairie grasslands; variability in surface reflectance was strongly related to canopy structural variables, but NDVI reduced BRDF effects over most SZA. Along–scan, east–west gradients were reported in reflectance over large, homogeneous areas like Amazonia, Congo Basin, and Australia (Toivonen et al., 2006). In a study of spatial patterns of reflectance in a tall-grass prairie, Goodin et al. (2004) urged caution in interpreting spatial structure derived from sensors with cross-track or off-nadir viewing angles and when comparing images acquired under varying illumination conditions. These cautions apply to varying illumination and viewing conditions as well as fusion of data between sensors with different viewing geometries.

With the goal of improving consistency in global land cover mapping and monitoring, several authors have proposed BRDF corrections for Landsat data. Danaher et al. (2001) discuss a BRDF correction technique using an empirical model derived from overlapping sequences of Landsat images, as well as a simple linear function of scan angle to mitigate the along-scan gradient (Wu et al., 2001; Danaher et al., 2001). Direct or indirect use of MODIS-based BRDF parameters to correct Landsat-estimated reflectance has also been explored (Roy et al., 2008; Li et al., 2010; Flood, 2013). Amidst the increasing accuracy of Landsat-based land-cover datasets and the variety of solutions for correcting BRDF effect, the problem itself remains poorly characterized.

In this paper, we investigate the seasonal magnitude and latitudinal variation of BRDF effects in Landsat reflectance and vegetation indices by simulating Landsat-5 Thematic Mapper (TM) reflectance estimates given the Landsat-5 orbit and MODIS based surface properties (reflectance and BRDF parameters) (Fig. 2). The simulation environment isolated the study of BRDF issues from other sources of variation (e.g., land-cover change, atmospheric interference, cloud contamination, and sensor degradation). To assess latitudinal differences, the study was carried out at one site for each of low, mid, and high latitudes (i.e., "tropical", "temperate", and "boreal" sites, respectively). Although the analysis is based on the long-term records of Landsat-5 overpass geometry, the conclusions will apply equally to the similar radiometric and orbital characteristics of Landsat-7 Enhanced Thematic Mapper Plus (ETM+) and the Operational Land Imager (OLI) aboard the newly launched Landsat-8 satellite (Loveland and Dwyer, 2012).

2. Data and methods

Landsat-5 TM reflectance time series were simulated at three 5×5-km sites using surface reflectance and BRDF parameters derived from 0.05° ($\sim$5-km) resolution MODIS Aqua and Terra Climate Modeling Grid (CMG) data (MOD09CMG) and sun-target-sensor geometry metadata obtained from the USGS Landsat archive (Figs. 2 and 3). The primary reason for using MODIS CMG $\sim$5-km product was the reliance of BRDF parameter estimation process on off-nadir views. An off-nadir pixel at VZA = 55° can have more than three times the projected area of a pixel at nadir VZA, due to increase in the effective pixel size with increasing view zenith angle. Moreover, a large portion (some times as much as 50%) of the electromagnetic radiation used by the sensor to estimate the radiometric properties of a pixel can come from surrounding pixels. Depending on atmospheric conditions, the adjacency effect can be as far as 1 km. There are also geo-location errors in MODIS data due to the use of a fixed global grid (Campagnolo and Montaño, 2014). Most of these issues present in MODIS products at native resolution are resolved by aggregation to a coarser spatial resolution, which produces a more stable signal for reliable BRDF parameter inversion. The standard 5-km resolution CMG product available from NASA was adopted for this analysis.

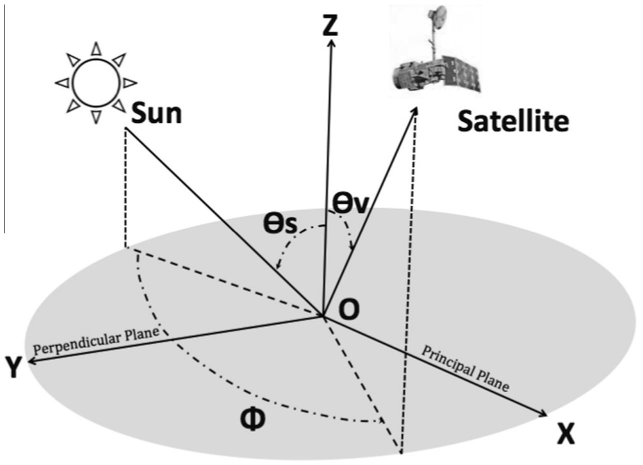

Fig. 1. Sun-target-sensor-geometry: Solar Zenith Angle (SZA), View Zenith Angle (VZA), and Relative Azimuth Angle (RELAZ).

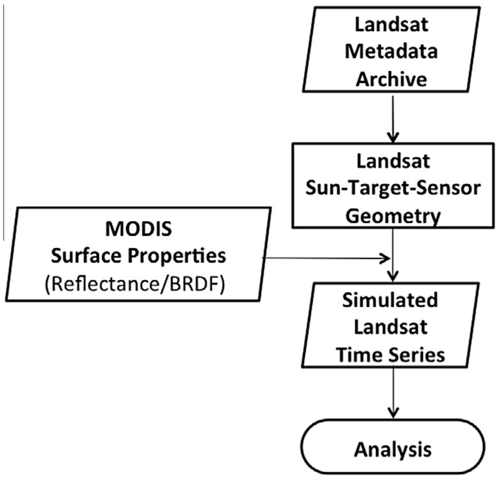

Fig. 2. Workflow for generation of simulated Landsat time series.

Please cite this article in press as: Nagol, J.R., et al. Bidirectional effects in Landsat reflectance estimates: Is there a problem to solve? ISPRS J. Photogram. Remote Sensing (2014), http://dx.doi.org/10.1016/j.isprsjprs.2014.09.006