Evaluation of Topographic Correction on Subpixel Impervious Cover Mapping With CBERS-2B Data

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***Abstract*—This study compared the effectiveness of six commonly used topographic correction methods for subpixel impervious surface mapping in selected mountainous areas of Southwest Virginia. One 2008 China–Brazil Earth Remote Sensing 2B (CBERS-2B) image was processed using selected topographic algorithms and then used as input for subpixel impervious cover mapping. High-resolution National Agriculture Imagery Program (1-m resolution) images were used to build proportional subpixel impervious cover as training/validation data. We then applied a classification and regression tree algorithm to establish relationships between CBERS signals and impervious surfaces. Accuracy assessment showed that both R^2 (0.644–0.767) and RMSE (0.118–0.150, reported as proportion of impervious surface) values vary across different topographic correction algorithms. The accuracy differences (R^2: 0.448–0.771; RMSE: 0.118–0.247) were most pronounced for areas facing away from the sun azimuth angle, suggesting aspect–sun azimuth-dependent map accuracy. For terrain shadowing areas, the Minnaert method, the minslope method, and the C-correction substantially outperformed the cosine and improved cosine correction. These findings indicate that users should apply caution in using topographic correction algorithms and that aspect-stratified accuracy assessment needs to be conducted for detailed comparisons. We also repeated the analyses using Landsat TM and obtained better overall results compared to the CBERS-2B data. The differences in R^2 (or RMSE) for two data sources were not substantial, suggesting the high potential of CBERS data for subpixel impervious surface mapping.**

***Index Terms*—Accuracy assessment, China–Brazil Earth Remote Sensing 2B (CBERS-2B), impervious cover, topographic correction.**

I. Introduction

Assessment of land use and land cover change in mountainous regions presents many important challenges for the remote sensing community, including terrain shadowing, high relief, cloud cover, and limited field data support. In mountainous regions, impervious surfaces, an important indicator of urbanization, are spatially dispersed, limited in aggregate area, and may be masked by shade or canopy. Furthermore, when observed at medium spatial resolution (e.g., Landsat, 30 m), impervious surfaces may be mixed with other land covers [1]. Spectral mixtures and spectral confusion impose significant difficulties for robust mapping of impervious surfaces.

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A number of topographic correction algorithms have been developed to reduce topographic impacts, and most of them require an ancillary digital elevation model (DEM) [2], [3]. For example, the cosine method [4], one of the most commonly used topographic correction algorithms, relies on DEM, solar zenith angle, and solar azimuth angle to model illumination conditions. The reflectance for an inclined surface is then adjusted by pixel illumination conditions to generate horizontal surface reflectance. Additional DEM-based topographic correction approaches include the empirical–statistical algorithms such as the C-correction [4] and the Minnaert method [5]. These two algorithms and their variations belong to the non-Lambertian empirical–statistical category. Model parameters, such as the Minnaert constant ($\mathrm{M_k}$) and C normalization term, need to be determined through ordinary linear regression [2]. For forested terrain, the Sun–Canopy–Sensor correction (SCS) algorithm was developed to incorporate tree canopy geometry and normalize the sunlit area within a pixel [6]. More recently, Lu *et al.* [7] have developed a pixel-based Minnaert correction method for reducing topographic effects on a Landsat 7 ETM image.

Several studies have compared the performances of different topographic correction algorithms [2], [3], [8]. One of the main criteria for the effectiveness of the algorithm is to see whether topographic correction reduces within-class spectral variation across varying terrain conditions. It appears that there is no universal best correction algorithm and correction performances vary for different study areas and applications. In addition, it is unclear how the reduced within-class spectral variation affects actual image classification accuracy. Few published studies reported overall and class-specific accuracy improvement. Compared to per-pixel image classification, subpixel mapping may be more sensitive to subtle changes in spectral reflectance. The interactions between topographic correction algorithms and subpixel classification accuracy have not been thoroughly examined.

The performance of topographic correction algorithms may also depend on remote sensing data. Landsat images are common data sources used for topographic corrections and comparisons. Currently, there is a growing interest of integrating multiple international satellite data sets to enhance the consistency and temporal resolution of the Landsat system [9]. For example, if Landsat data are supplemented by other sensor systems such as the China–Brazil Earth Remote Sensing (CBERS), Advanced Wide Field Sensor (AWiFS), and, in the near future, Sentinel-2 data, the temporal frequency of observation can be greatly improved. CBERS data are appealing because they provide Landsat-like spatial and spectral resolutions (visible and infrared bands). However, CBERS data have not been widely used outside Brazil and China. Image preprocessing procedures, such as atmospheric and topographic correction, are not well researched or referenced. More studies are needed to assess image preprocessing algorithms for future operational use of CBERS data.

The overall objective of this study was to evaluate impacts of several topographic correction algorithms on subpixel impervious surface mapping using CBERS data. Our study area is the city of Roanoke in the USA. It is the largest municipality in southwestern Virginia, USA. Roanoke covers a total area of 111.1 km^2 and has a total population of 97 032. It is located along Blue Ridge Mountains, where urban and residential developments have been well extended into hilly areas, offering an ideal location to examine impacts of topographic correction algorithms on subpixel impervious cover mapping.

II. Methods

A. Data

We obtained CBERS-2B satellite data from the Institute of Remote Sensing and Digital Earth (RADI), Chinese Academy of Sciences. Among all imagery obtained by several instruments onboard the CBERS satellite, the high-resolution charge-coupled device (CCD) image is most comparable to the Landsat data. The spatial resolution of the CCD image is 20 m, and the image swath is around 120 km. The CCD image has four spectral bands (blue, green, red, and near infrared) that are almost identical to those of Landsat TM data. One CCD image acquired on November 26, 2008, was used for this study. It is the only cloud-free image available for the study area.

One Landsat TM surface reflectance image (October 30, 2008) was downloaded from EarthExplorer (http://earthexplorer.usgs.gov/). The image was processed through the Landsat Ecosystem Disturbance Adaptive Processing System. Landsat standard terrain correction was previously applied; thus, no further geometric correction is needed. We also obtained the 1-m-spatial-resolution National Agricultural Imagery Program (NAIP) digital orthoimagery from the U.S. Department of Agriculture (USDA) Geospatial Data Gateway (http://datagateway.nrcs.usda.gov/). The 1-m NAIP image was acquired during the agricultural growing season of 2008 and covers the entire Roanoke city. The NAIP image was used to generate training/validation data for subpixel impervious cover mapping. In addition, a 30-m DEM was obtained from the USGS National Map Viewer and Download Platform.

B. CBERS-2B Image Preprocessing and Topographic Correction

For the CBERS-2B CCD image, we first conducted a global destriping [10], to remove the minor "stripe" effect. We then conducted image coregistration using the Landsat image as the base image. The original CBERS-2B image was rescaled to 30-m spatial resolution, to spatially match with the Landsat image. The 30-m resolution was also required to match the DEM spatial resolution. A simple dark-object subtraction (DOS1) method was used to reduce atmospheric impacts, and the digital numbers were converted to surface reflectance values based on the procedures suggested by Chavez [11]. The CBERS-2B surface reflectance image, Landsat image, and DEM were then spatially subset to cover the Roanoke city boundary.

TABLE I
CBERS-2B and Landsat TM Data Used for Subpixel Mapping

	Acquisition	Sun elevation	Sun azimuth
CBERS-2B	Oct 30, 2008	30.63	168.09
Landsat TM	Nov 26, 2008	34.89	155.26

A key step in most topographic correction algorithms is to model illumination (IL) condition through

$$\mathrm{IL} = \cos(t_s)\cos(\theta_z) + \sin(t_s)\sin(\theta_z)\cos(\mathrm{sun}_a - t_a) \quad (1)$$

where t_s and t_a are the terrain slope and aspect angles, respectively. θ_z is the solar zenith angle, and sun_a is the sun azimuth angle. IL can be then directly used to normalize surface reflectance or combined with additional parameters to derive horizontal surface reflectance. Specific equations and a more detailed review can be seen in [2].

We used the R Landsat package to implement topographic corrections. The R Landsat package includes a set of functions for radiometric and topographic corrections [13]. Although the package is named as Landsat, it is also suitable for processing Landsat-like remote sensing data. Among all available topographic correction algorithms in the Landsat package, we selected the cosine method, the improved cosine method [12], the Minnaert method, the C-correction, the minslope [2], and the gamma correction [3], for comparison. The SCS approach was not used because it was mainly designed for forested areas. The "topocorr" command in the Landsat package requires six input variables: spectral reflectance, slope, aspect, sun elevation angle, sun azimuth angle, and specific correction method. We derived slope and aspect images from the 30-m DEM. Sun elevation and azimuth values were directly obtained from image headers (see Table I). The users only needed to adjust the "method" parameter (e.g., cosine and improved cosine) to generate corrected surface reflectance values from different topographic correction algorithms. We streamlined the entire topographic procedure using R programming.

C. Subpixel Impervious Cover Mapping

We classified the 1-m NAIP image to impervious/nonimpervious cover through an object-based image analysis (OBIA) [14]. Fig. 1 shows the original NAIP image and the two-class classification map. Visual interpretation of NAIP-derived impervious cover suggested good overall performance. We conducted accuracy assessment for the NAIP-derived map using a stratified random sampling ($n = 100$). Overall, accuracy was 92%, and the user's accuracy for impervious cover was 82%. This 1-m-resolution impervious cover map was degraded to 30 m $\times$ 30 m resolution, to match the CBERS-2B and Landsat TM images. This impervious factional map was used to support training/validation of subpixel impervious cover mapping of CBERS-2B image.

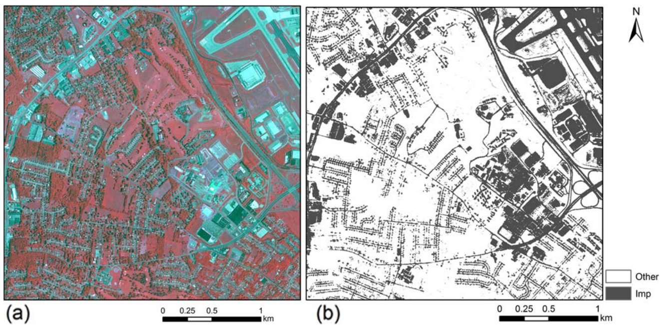

Fig. 1. Two-class (impervious and nonimpervious cover) classification results with NAIP image. The original NAIP image (left) is included as reference.

Topographically corrected CBERS-2B surface reflectance values were used as input for subpixel impervious surface mapping. A total of 5000 training data points were randomly selected from relatively flat areas (i.e., slope $< 5°$). The main reason to select training data points from relatively flat surfaces was to assess if a trained subpixel classifier could be generalized across space, particularly for sloped areas with varied spatial aspects. A good topographic correction algorithm should be able to "recover" horizontal surface reflectance values or reduce the topographic influence in sloped areas.

We used a classification and regression tree (CART) to model relationships between topographically corrected CBERS-2B surface reflectance values and subpixel impervious proportions. CART has been widely used for subpixel research, and it was the key algorithm used for subpixel impervious surface and tree canopy map products in the U.S. 2001 National Land Cover Database (NLCD) [15]. Since we generated six sets of surface reflectance values from different topographic correction methods, the subpixel mapping training was conducted six times, independent of each other. For each training task, tree pruning was used to reduce sizes of decision trees; optimal tree sizes were determined by fivefold cross-validation. The trained CART was then applied to the entire image, to generate subpixel impervious surface maps.

To evaluate whether various topographic corrections improved subpixel classification, we used the surface reflectance of the CBERS-2B image without topographic correction as an alternative input for the subpixel mapping. Furthermore, we implemented subpixel mapping using Landsat surface reflectance data. This strategy allowed us to compare subpixel classification performances across two different sensors.

D. Accuracy Assessment

A total of eight subpixel impervious surface maps were derived, including results from uncorrected surface reflectance of CBERS-2B image, six different topographic corrections for CBERS-2B image, and Landsat image. To reduce possible impacts of image misregistration [16], all subpixel maps were aggregated to 90-m resolution and compared to a spatially aggregated NAIP impervious map (90-m resolution). A total of 5000 90-m image windows were randomly selected for accuracy assessment. The root-mean-square error (RMSE) and R^2 statistics were computed and compared for various topographic correction methods.

TABLE II
CBERS-PREDICTED IMPERVIOUS SURFACE MAPS WERE COMPARED TO THE NAIP IMPERVIOUS MAP. HERE, R^2 VALUES ARE PRESENTED FOR THE ENTIRE VALIDATION SET AND ASPECT-STRATIFIED PIXELS

Aspect	raw	cos	icos	minn	c_cor	mslope	Gamma
0-45	**0.739**	**0.555**	**0.674**	**0.797**	**0.796**	**0.806**	**0.766**
45-90	0.768	0.684	0.715	0.767	0.766	0.770	0.749
90-135	0.767	0.714	0.733	0.776	0.776	0.780	0.731
135-180	0.765	0.724	0.724	0.776	0.776	0.777	0.731
180-225	0.733	0.683	0.689	0.744	0.743	0.746	0.698
225-270	0.748	0.685	0.713	0.754	0.746	0.750	0.719
270-315	0.730	0.543	0.651	0.741	0.753	0.755	0.720
315-360	**0.711**	**0.448**	**0.655**	**0.771**	**0.745**	**0.761**	**0.759**
Overall	0.752	0.644	0.686	0.764	0.763	0.767	0.724

TABLE III
CBERS-PREDICTED IMPERVIOUS SURFACE MAPS WERE COMPARED TO THE NAIP IMPERVIOUS MAP. RMSE IS PRESENTED FOR THE ENTIRE VALIDATION SET AND FOR ASPECT-STRATIFIED PIXELS

	raw	cos	icos	minn	c_cor	mslope	Gamma
0-45	**0.131**	**0.213**	**0.178**	**0.115**	**0.115**	**0.113**	**0.126**
45-90	0.118	0.147	0.138	0.118	0.118	0.117	0.122
90-135	0.121	0.133	0.128	0.117	0.117	0.116	0.130
135-180	0.122	0.132	0.132	0.119	0.119	0.119	0.132
180-225	0.125	0.136	0.135	0.122	0.123	0.122	0.135
225-270	0.120	0.137	0.130	0.118	0.120	0.119	0.127
270-315	0.117	0.181	0.152	0.115	0.112	0.111	0.119
315-360	**0.133**	**0.247**	**0.188**	**0.118**	**0.123**	**0.120**	**0.123**
Overall	0.122	0.150	0.139	0.118	0.119	0.118	0.129

Subpixel maps derived from different topographic corrections may show different error distributions across space. For example, sun-facing and terrain shadowing areas may have very different accuracy statistics. Certain topographic correction algorithms may overcorrect surface reflectance values for terrain shadowing areas [2], which can lead to uneven or terrain-specific map accuracy. We conducted additional accuracy assessment by stratifying validation data points by topographic aspects. Aspect is measured clockwise $(0° - 360°)$ starting from due north. We considered eight aspect zones (starting from $0°$, and $45°$ each) and calculated RMSE and R^2 statistics for each validation zone. This aspect-based stratification allowed us to evaluate how accuracy statistics change, corresponding to terrain and sun azimuth angle.

III. RESULTS AND DISCUSSION

A. Topographic Correction Impacts on Subpixel Impervious Cover Mapping

The accuracy values of CBERS-2B subpixel maps are summarized in Tables II and III. For the entire study area, R^2 values for six selected topographic correction algorithms were in the range of 0.644–0.767. The corresponding RMSE values were 0.118–0.150 (proportion of impervious surface). The cosine method performed worst among all topographic correction algorithms. R^2 value (0.644) was lower than the uncorrected CBERS data ($R^2 = 0.752$). The improved cosine and Gamma algorithms also generated lower R^2 values and higher RMSE values compared to the uncorrected CBERS data. The Minnaert method, the C-correction, and the minslope approach generated improved subpixel classification results compared to the uncorrected data. However, the R^2 values (0.764, 0.763, and 0.767) for the three algorithms are only slightly higher than the results from the uncorrected CBERS data. The differences in RMSE values were also quite small and might not be meaningful in practice.

The main difference of topographic correction algorithms and their impacts on subpixel mapping can be observed from aspect-stratified accuracy statistics. For example, for areas with $0^\circ - 45^\circ$ aspect values, the R^2 value for the uncorrected CBERS data was 0.739 (RMSE $= 0.131$); the R^2 values increased to 0.797 (RMSE $= 0.115$), 0.796 (RMSE $= 0.115$), and 0.806 (RMSE $= 0.113$) for the Minnaert method, the C-correction method, and the minslope method, respectively (see Tables I and II). The cosine and improved cosine algorithms appeared to be not effective for this aspect zone (0°–45°). R^2 values were 0.555 and 0.674 for the two algorithms, and both values were substantially lower than those derived from the uncorrected and other topographic correction algorithms. Similar classification accuracy patterns were observed for the aspect zone of 315°–360°, where R^2 values varied from 0.448 to 0.771 (RMSE, 0.118–0.247) across different correction algorithms. The accuracy statistics for other aspect zones were more consistent among different correction algorithms. For example, for the aspect zone of 135°–180°, R^2 values were in the range of 0.724–0.777 (RMSE, 0.119–0.132).

For this specific CBERS image, the sun azimuth angle was 168°. The areas with aspect degrees of 0–45 and 315–360, thus, are facing away from the sun, and illumination was relatively low. The cosine and improved cosine methods, although widely used in remote sensing community, may overcorrect the surface reflectance values for areas with low illumination [2], resulting in questionable subpixel impervious estimation. Three empirical–statistical methods, i.e., the Minnaert method, the minslope, and the C-correction, improved subpixel mapping results for low-illumination areas and, thus, achieved relatively even subpixel mapping accuracy across different aspect zones.

Fig. 2 shows the scatterplots of NAIP-derived impervious surface proportions and CBERS-predicted impervious proportions for two selected topographic correction methods (the cosine and minslope methods). To highlight aspect-dependent accuracy distribution, we only presented the validation points located within the 0°–45° aspect zone. The subpixel mapping results for the cosine correction show a large degree of scatter. The main issue was the overestimation of impervious surface for pixels with relatively low impervious proportions (e.g., $< 20\%$). The results from the minslope algorithm appeared to be much better. Points are more tightly clustered around the $1:1$ line, suggesting good agreement between CBERS-predicted and NAIP-derived impervious maps.

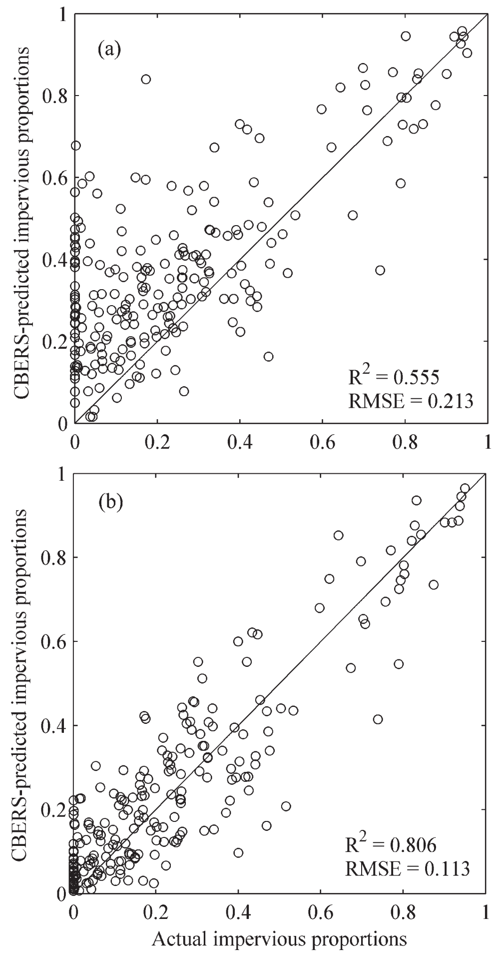

Fig. 2. Comparison of subpixel mapping results from two selected topographic corrections. (a) The cosine method and (b) the minslope method.

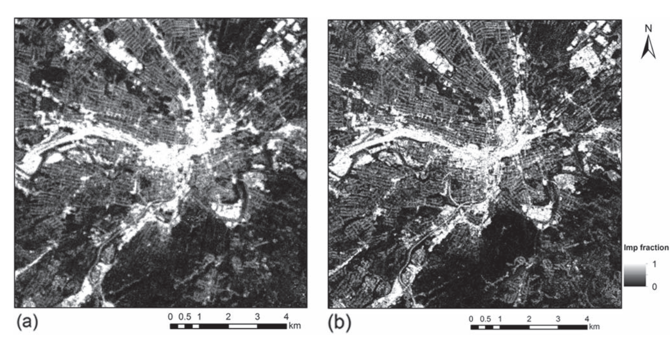

Fig. 3. Comparison of subpixel mapping results from CBERS-2B (minslope correction, left image) and Landsat images (right image).

B. CBERS Versus Landsat for Subpixel Mapping

Fig. 3. shows CBERS- and Landsat-predicted subpixel impervious maps. Only a subset of study area is presented for easier visual comparison. The CBERS-derived map was from the minslope algorithm. Although both maps show similar urban features, the Landsat-derived impervious surface shows better detail for high-density commercial areas, street networks, and residential areas. We also conducted accuracy assessment for the Landsat-derived impervious surface map, using the NAIP impervious map as reference. The R^2 and RMSE values for the Landsat-derived map were 0.801 and 0.109, respectively. Additionally, the aspect-stratified accuracy ranged from 0.779 to 0.820 (RMSE, 0.103–0.113). Superior subpixel mapping

results from Landsat data were expected for several reasons. First, additional spectral bands in the Landsat image provide more spectral information to delineate impervious surface. Second, the Landsat scene was acquired on October 30, while the CBERS image was acquired on November 26. Phenological or seasonal differences may contribute to different classification performances. We also note that future studies need to compare subpixel mapping results from CBERS and uncorrected Landsat data, as well as topographically corrected Landsat data from various correction algorithms.

Although this CBERS image generated a less accurate subpixel map compared to the Landsat data, differences were not substantial (R^2 difference around 0.05 and RMSE difference around 0.01). Therefore, the CBERS-derived subpixel map may still be useful for supplementing U.S. NLCD products to improve temporal resolution or fill data gaps [9].

IV. Conclusion

Six topographic correction algorithms have been compared for their effectiveness in subpixel impervious surface mapping using CBERS-2B imagery. Empirical–statistical algorithms, such as the Minnaert method, the minslope, and the C-correction, outperformed the cosine and improved cosine corrections. These three empirical–statistical algorithms also significantly improved the mapping accuracy relative to no correction, particularly for areas with slopes that face away from the sun. This finding suggests that topographic corrections are important for subpixel mapping to avoid systematic errors introduced due to differing illumination conditions. This study also highlights the aspect-stratified accuracy assessment. Furthermore, we found that CBERS-based subpixel mapping generated slightly lower accuracy compared to Landsat-based mapping. Further studies are needed to fully evaluate the use of CBERS data to improve temporal resolution of Landsat-based land use and land cover products.

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