Estimating Nitrogen in Eucalypt Foliage by Automatically Extracting Tree Spectra from HyMap™ Data

Zhi Huang, Xiuping Jia, Brian J. Turner, Stephen J. Dury, Ian R. Wallis, and William J. Foley

Abstract

Airborne HyMap™ data obtained from the crown reflectance of Eucalyptus melliodora *were used to estimate nitrogen in the foliage. Estimating chemical concentrations in individual crowns by remote sensing is especially difficult for eucalypts because, first, there is marked variation between individual crowns and, secondly, separating leaf and background spectral information is difficult. We developed an automatic method to select relatively pure tree pixels for each tree. In this method, the background materials are modeled, and the pixels within a crown that do not resemble the background clusters are regarded as target pixels. A modified partial least squares gave an R^2 value for predicted versus determined nitrogen concentrations of 0.79, with an RMSE of 0.69 mg/g, less than half the standard deviation of the measured values. Automatically selecting tree pixels was more accurate than manual selection, while the study confirmed that using the maximum spectrum gives results that are as accurate as those from the mean spectrum.*

Introduction

Measuring foliar biochemical concentrations traditionally involves a chemical analysis that is often hampered by limitations on time and resources, making it impractical for surveying large areas. On the other hand, multispectral, and especially hyperspectral remotely sensed data are showing promise as an inexpensive and quick alternative to chemical analyses. Unfortunately, estimating foliar biochemical concentrations from crown reflectance collected by airborne and spaceborne imaging spectrometers is difficult. Problems include significant radiometric distortion due to atmospheric effects, low signal to noise ratio, complicated tree crown characteristics, and large background effects (e.g., Yoder and Pettigrew-Crosby, 1995; Matson *et al.*, 1994). Even so, there has been recent success in estimating foliar nitrogen concentration from airborne remote sensing data, such as AVIRIS and spaceborne Hyperion data (e.g., Johnson *et al.*, 1994; Matson *et al.*, 1994; LaCapra *et al.*, 1996; Martin and Aber, 1997; Coops *et al.*, 2003; Smith *et al.*, 2002 and 2003). These studies, however, depended on extracting reflectance spectra either from averaging pixels of study plots or from measuring reflectance over homogeneous areas. This is inappropriate for those interested in the chemical concentrations of individual trees, especially eucalypts.

It is known that two factors, food quality and shelter, largely determine habitat quality for folivorous marsupials (Pausas *et al.*, 1995). As shown by several recent studies (Lawler *et al.*, 2000; Wallis *et al.*, 2003; Moore *et al.*, 2004), eucalypts show considerable within-species variation in their concentrations of certain chemicals. This almost certainly explains the patchiness in both occurrence and abundance of folivorous marsupials in eucalypt forests and woodlands (Braithwaite *et al.*, 1984). Therefore, the challenge is to develop rapid and affordable techniques that enable us to measure the chemistry of individual trees over entire landscapes. Such a technique would be invaluable in studying the distribution of marsupial folivores and in tracking changes in foliar chemistry with climate change. The study described in this paper is one of the few to take up the challenge.

Apart from the wide variation between trees in the concentration of chemical compounds, eucalypt forests have unique crown characteristics that pose difficulties in estimating subtle foliage biochemical concentrations from remotely sensed data (Turner *et al.*, 1998). Eucalypt leaves are often pendulous and usually evergreen while juvenile leaves may differ both physically and chemically from adult leaves. Furthermore, eucalypt canopies tend to be relatively open and show lower crown reflectance and greater background effects than do the spectra from many other tree

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genera. This makes it difficult to be certain about picking pure pixels of foliage from remote sensing images to represent the tree, a necessary step before statistical processes can occur. However, a compromise is to find a routine way to select pixels that are nearly pure. These pixels, which are largely free of background effects, are referred to as "relatively pure tree pixels."

Huang *et al.* (2004) manually selected relatively pure tree pixels from HyMap™ data. They did this by locating individual trees on a hardcopy false color HyMap™ image, confirming their identity through a field inspection, then carefully identifying and separating tree pixels from surrounding pixels for each tree manually using computer selection. This is easy because the tree pixels are a different shape and color to the background in the false color image. But, this method has drawbacks. One is that the manual method could utilize the data from only three out of 125 HyMap™ bands in the selection process. A lesser problem is that the manual extraction is prone to human error.

One way to automate the selection process would be to apply mixed pixel analysis, such as endmember decomposition (Adams *et al.*, 1986). However, an endmember signature for pure foliage is not available from these HyMap™ data since the tree pixels are usually contaminated by the background effects and cannot be located as training data. This makes spectral unmixing impossible.

The aim of this study was to develop an automatic method for selecting relatively pure tree pixels using all spectral bands, by deriving spectral classes for the background and assuming that the relatively pure tree pixels are those most spectrally different from the background pixels. After selecting relatively pure tree pixels of a single tree, it is usual to denote the mean spectrum as the representative reflectance spectrum for that tree. However, Huang *et al.* (2004) suggested that deriving maximum spectra might provide better estimates of subtle biochemical features. Thus, we used a modified partial least squares method (Wold, 1982; Shenk and Westerhaus, 1991) to estimate the foliar nitrogen concentrations of individual trees estimated from both mean and maximum spectra.

Methods

Data Collection and Preprocessing

Leaf samples from the upper crown of 60 trees of *Eucalyptus melliodora* were collected over two days in April 1999 from open woodland approximately 20 km east of Canberra, Australia. The ground typically had a sparse cover of dry grass interspersed with patches of bare earth. We selected this site for three reasons. First, a traversing road made it easy to map the individual trees. Secondly, we had collected foliage from many of the trees before for other studies (e.g., Wallis *et al.*, 2002). Finally, it was easy to select roughly 60 large trees (dbh > 90 cm; crown diameter exceeding 10 m) with crowns that did not overlap. This avoided the possibility of misidentifying crowns. All samples were of fully expanded adult foliage from the mid- to upper-crown. Leaf nitrogen concentrations were determined from freeze-dried leaves using the semi-micro Kjeldahl technique. They ranged from 9.8 to 17.8 mg/g DM (Dry Matter), with a mean of 14.35 mg/g DM and a standard deviation of 1.52 mg/g DM, respectively. Airborne HyMap™ (Hyperspectral Mapping) data of the study area were obtained at roughly midday, in April 1999, one and two days before sampling the foliage. HyMap™ data have 128 spectral bands over the 0.40 to 2.5 micrometer wavelength range and a spatial resolution of 3 × 3 meters, sufficient to identify individual trees on the ground (Figure 1). We removed three bands, Band 1 (431 nm), Band 2 (444 nm), and Band 32 (893 nm), that contained corrupted data.

Figure 1. HyMap™ image of a subset of the study area. A color version of this figure is available on the ASPRS website: **www.asprs.org.**

The preprocessing of HyMap™ data occurred in several steps. The first was to convert the original Digital Number (DN) to radiance using the DN-to-radiance conversion factors that accompanied HyMap™ data. The next task was atmospheric correction. By investigating several atmospheric correction methods, we discovered that the program, Hycorr, a modified ATREM program combined with an EFFORT procedure (Boardman, 1998), gave the best results (Huang *et al.*, 2004). It largely removed the water vapor absorption to produce a spectrum resembling that of fresh whole leaves measured with a field spectrometer.

The Extraction of Relatively Pure Tree Pixels

We developed an automatic method to select relatively pure tree pixels from the crown pixels of individual trees. This method is mostly computer-driven and uses information from all 125 HyMap™ bands. The rationale for selecting relatively pure tree pixels is that if a pixel is very spectrally dissimilar to all of the known background classes, then it is believed to represent the tree's foliage. Two assumptions are made in the proposed method:

1. pixels are either tree pixels or one of the background classes, and
2. each background class has a hyperspherical distribution in the hyperspectral feature space.

To implement this idea, we developed the following steps with particular attention to meeting the assumptions. First, the candidates for the tree pixels, ranging from 8 to 28 pixels per tree, were selected from around and within a tree crown. This is easy to define manually on a false color HyMap™ image, so that each pixel is either a tree pixel or a pixel from one of the background classes. This is shown in Figure 1, a small region of the color composite image. It can be seen that the background materials are the combination of "soil," "grass," and "shadow" in various proportions. Therefore, these three endmembers are defined as background classes. They were trained with a supervised approach using training fields selected from the image. Due to the high variation of each background class, the spectra

were represented as a group of homogeneous subclasses. We used each background training data set to generate a set of clusters with the clustering algorithm of ISODATA (Richards and Jia, 1999) on all of the available spectral bands. Full spectral information was utilized and enough clusters generated to ensure that each cluster had low spectral variation. As a result, the generated spectral classes (subclasses) meet the second assumption of hyperspherical distributions. Cluster mean vectors, $\mathbf{m}_{ik}$, $i = 1, \ldots 3$, $k = 1, \ldots K_i$, are formed as background spectral class signatures, where K_i is the number of subclasses for class i. Similarity measures were based on Euclidean distance, i.e.,

$$d(\mathbf{x},\mathbf{m}_{ik}) = (\mathbf{x} - \mathbf{m}_{ik})^t (\mathbf{x} - \mathbf{m}_{ik}) \quad (1)$$

where $\mathbf{x}$ is the pixel vector of interest, and t denotes the transpose operation. The decision rule for selecting a relatively pure tree pixel is then defined as:

$$\text{if } d(\mathbf{x},\mathbf{m}_{ik})_{\min} \geq d(\mathbf{x}_b,\mathbf{m}_{ik})_{\min},$$

then $\mathbf{x}$ is the spectral data of a relatively pure tree pixel; where $i = 1, \ldots 3$, $k = 1, \ldots K_i$, and $b = 1, \ldots L$, where L is the number of pixels to examine for the tree of interest. In other words, compared to all of the other pixels within a tree crown or its surroundings, a relatively pure tree pixel is most spectrally distant from the closest background spectral class. In this study, all of the trees had large canopies, which enabled us to select three pixels for each tree. Selecting more than one tree pixel for each tree generates a more reliable spectrum and minimizes background effects.

A variant of the method for selecting tree pixels is to determine the correlation between candidate pixels and the spectrum of each background class and assume that the lowest correlation indicates strong dissimilarity. The correlation between a pixel vector "$\mathbf{x}$" and a background spectral class "$\mathbf{m}_{ik}$" is calculated as:

$$r(\mathbf{x},\mathbf{m}_{ik}) = \frac{(\mathbf{x} - \bar{\mathbf{x}})^t (\mathbf{m}_{ik} - \bar{\mathbf{m}}_{ik})}{\sqrt{(\mathbf{x} - \bar{\mathbf{x}})^t (\mathbf{x} - \bar{\mathbf{x}}) (\mathbf{m}_{ik} - \bar{\mathbf{m}}_{ik})^t (\mathbf{m}_{ik} - \bar{\mathbf{m}}_{ik})}} \quad (2)$$

where $\bar{\mathbf{x}}$, $\bar{\mathbf{m}}_{ik}$ are the average values of the spectral reflectance over all the spectral bands for the pixel vector "$\mathbf{x}$" and the mean spectrum of a subclass "$\mathbf{m}_{ik}$", respectively. The related decision rule is then:

$$\text{if } r(\mathbf{x},\mathbf{m}_{ik})_{\max} \leq r(\mathbf{x}_b,\mathbf{m}_{ik})_{\max},$$

then $\mathbf{x}$ is a relatively pure tree pixel; where $i = 1, \ldots 3$, $k = 1, \ldots K_i$, $b = 1, \ldots L$, where L is the number of pixels to examine for the tree of interest.

The correlation measure differs from the Euclidean distance measure by normalizing the magnitude differences of the reflectance. This helps if the shape of the spectrum is the only significant factor for differentiating classes. Both measures were tested in our experiments.

Deriving Tree Spectra

The three relatively pure tree pixels from each tree were used to generate tree spectra. As usual, averaging the three spectra derived a mean spectrum. However, this may be inappropriate in species, like many eucalypts, with complicated tree crown structures that cause wide differences in canopy illumination. Thus, we also obtained a reflectance spectrum representing a brightly lit part of a tree crown by selecting the highest reflectance of each spectral band among the three original tree spectra. The results for the maximum spectra (Huang *et al.*, 2004) were compared with those using mean spectra.

In summary, for each of the 60 tree samples, we statistically analyzed four spectral data sets. They were: (a) the mean, (b) the maximum spectra created from the Euclidean distance approach (MeanMD, MaxMD), (c) the mean, and (d) the maximum spectra created from the correlation approach (MeanCOR, MaxCOR). Before statistical analyses, the four sets of reflectance data (R) were transformed into the log ($1/R$) format to represent the associated absorption spectra.

Statistical Analysis Methods

The data were analyzed using modified partial least squares (MPLS) (Wold, 1982) implemented with the WinISI package (Infrasoft International, 2001). We selected a maximum of six factors to prevent overfitting. Given the limited number of samples, we did not use independent test samples to measure the effectiveness of the models, but instead used cross-validation (Anonymous, 1995; Shenk and Westerhaus, 1991).

Results

The statistical results of the four experiments are summarized in Table 1 in terms of the coefficient of determination (R^2), standard error of cross-validation (SECV) and root mean square error (RMSE), while the estimated versus measured nitrogen concentrations are shown in Figures 2 through 5. The potential of the method is shown by the SECV: all four methods gave results within one standard deviation of the measured nitrogen concentration. Even so, some methods proved better than others. The best relationship between predicted and measured nitrogen concentrations came from the MaxCOR approach ($R^2 = 0.79$; SECV = 1.37 mg N per g DM; RMSE = 0.69 mg N per g DM), even though it had one clear outlier (see Figure 5) that we cannot explain. Indeed, the maximum spectra consistently gave higher R^2 values than did the mean spectra. Of the two similarity measures used for selecting relatively pure tree pixels, the correlation proved slightly better than the Euclidean distance for the data from the maximum spectra, but markedly better for the spectral mean data.

To evaluate whether it is better to automatically or manually select tree pixels, the results of previous tests (Huang *et al.*, 2004) with manually-selected pixels are given in Table 1 as MeanMAN and MaxMAN. Apart from the abovementioned poor result for the Euclidean distance selection of the mean data, the automatic pixel selection method increases the coefficients of determination (R^2) and gives SECV and RMSE values that are as low as those from the manual method.

Discussion and Conclusion

This study showed that by using spectral information from relatively pure tree pixels we could accurately predict the foliar nitrogen concentrations of individual trees.

TABLE 1. THE COEFFICIENT OF DETERMINATION (R^2), THE STANDARD ERROR OF CROSS VALIDATION (SECV) AND THE ROOT MEAN SQUARE ERROR (RMSE) OF ESTIMATES OF THE NITROGEN CONCENTRATION OF EUCALYPT CANOPIES. THREE DIFFERENT METHODS, A EUCLIDEAN DISTANCE (MD), A CORRELATION (COR), AND A MANUAL METHOD (MAN), WERE USED TO EXTRACT RELATIVELY PURE TREE PIXELS FROM BOTH MEAN AND MAXIMUM (MAX) SPECTRA

Spectra Applied	R^2	SECV	RMSE
MeanMD	0.44	1.29	1.13
MeanCOR	0.65	1.40	0.89
MeanMAN	0.51	1.46	1.05
MaxMD	0.73	1.39	0.79
MaxCOR	0.79	1.37	0.69
MaxMAN	0.65	1.35	0.90

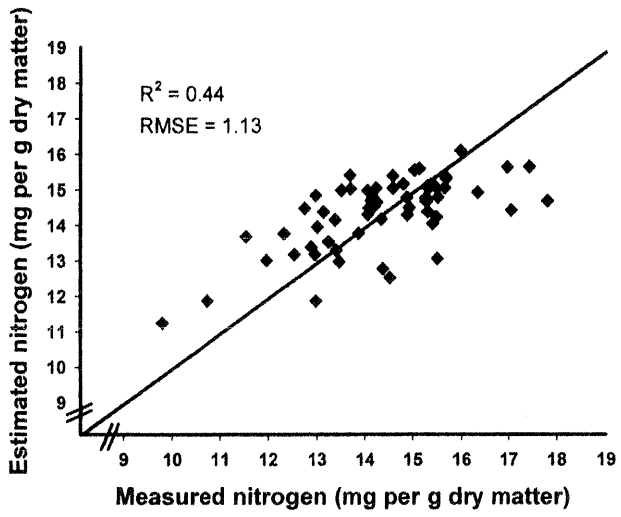

Figure 2. The nitrogen concentrations in eucalypt canopies predicted with a modified partial least squares statistic using tree pixels extracted from the mean spectra by the Euclidean distance method.

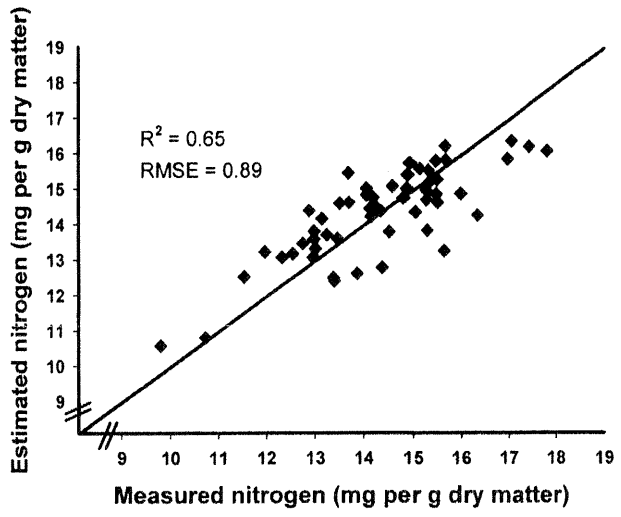

Figure 4. The nitrogen concentrations in eucalypt canopies predicted with a modified partial least squares statistic from tree pixels extracted from the mean spectra by the correlation method.

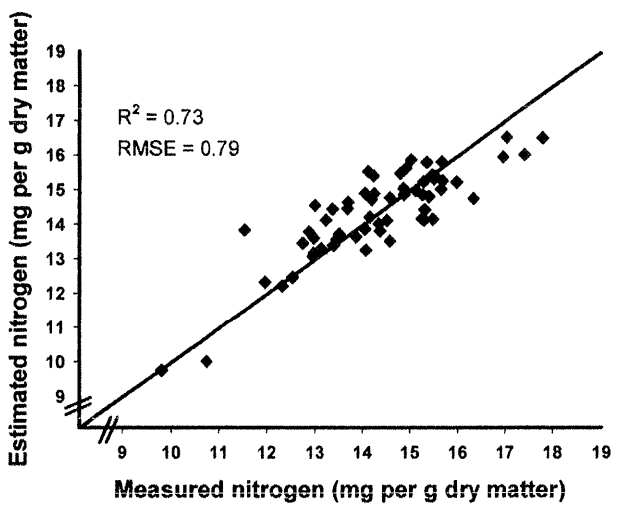

Figure 3. The nitrogen concentrations in eucalypt canopies predicted with a modified partial least squares statistic from tree pixels extracted from the maximum spectra by the Euclidean distance method.

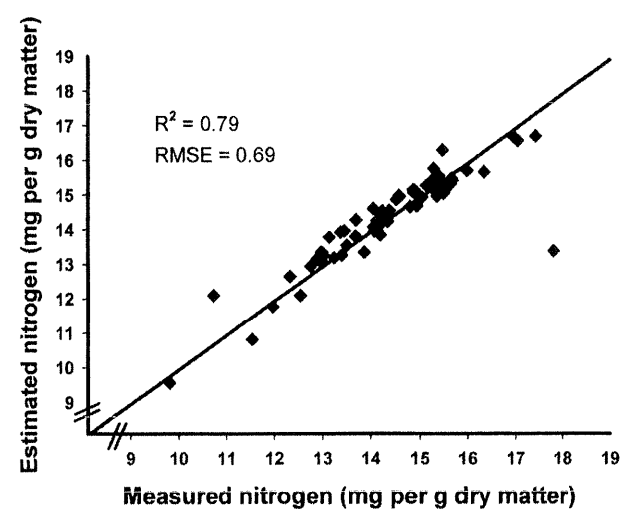

Figure 5. The nitrogen concentrations in eucalypt canopies predicted with a modified partial least squares statistic from tree pixels extracted from the maximum spectra by the correlation method.

The automatic method of selecting relatively pure tree pixels from a complicated tree crown is a better approach than the manual method, even though the latter provides a reasonable estimate of foliar nitrogen when used with spectral maximum data. This is not surprising. As pointed out in the introduction, the automatic method uses all of the spectral information from HyMap™ and excludes the possibility of human error during the manual selection of pure pixels. Thus, we recommend using the automatic method to select tree pixels in future applications.

Of the two automatic approaches for selecting relatively pure tree pixels, the correlation measure proved better than the method based on the Euclidean distance. The likely explanation for this is that the correlation has normalized the magnitude of the difference of reflectance between the pixels of interest. This shows that, when classifying a pixel into a class, the shape of its spectrum is a better indicator of classification accuracy than is its distance to the mean of the class. In estimating nitrogen concentrations, the maximum spectra yielded higher R^2 values than did the mean spectra. Presumably, this indicates that where large illumination differences exist within a tree crown, the maximum spectrum better represents the crown spectrum than does the mean spectrum.

This study reinforces our earlier finding that airborne HyMap™ data can be used to estimate foliar nitrogen concentrations in the crowns of individual eucalypt trees. The well-known confounding factors in extending estimates from those of whole leaves to entire canopies can be ameliorated by applying a comprehensive atmospheric correction, by automatically selecting relatively pure tree pixels and by deriving both mean and maximum spectra.

We chose nitrogen as a model element because it can be measured very accurately with spectral procedures. Also, it is often viewed as a useful indicator of landscape fertility and thus animal abundance (e.g., White, 1993). As Moore *et al.* (2005) argue, animal abundance in eucalypt forests is much more complex than a simple function of the nitrogen concentration in the leaves. For example, a large number of defensive chemicals in foliage are probably important too. This is something realized by Braithwaite *et al.* (1984), who attempted large-scale studies of forest chemistry, using traditional chemical analyses, and thus became influential in debates on forest conservation. The "proof of concept" shown in the current work is a logical progression from the research of Braithwaite *et al.* (1984) and suggests that it will be possible to map the nutritional environment of eucalypt forests and woodlands from the air. Apart from the obvious advantages that remote sensing bestows on studies of animal distribution and abundance, it will be even more valuable in tracking subtle changes in forest chemistry and composition, for instance, those associated with climate change.

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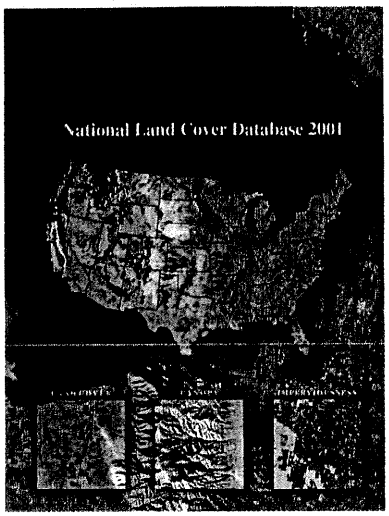
This month's cover shows the completed National Land Cover Database 2001 (NLCD 2001) for the conterminous United States. NLCD 2001 contains 3 primary Landsat-based products: percent tree canopy, percent urban imperviousness, and 16 classes of land cover, all at 30 meter cell resolution from nominal year 2001 imagery. On the cover, the land cover product is displayed nationally against a background of Landsat 7 ETM+ leaf-on imagery for the area around Salt Lake City, Utah. Actual subsets of NLCD 2001 urban imperviousness, tree canopy, and land cover segments from this region are highlighted in full color boxes to demonstrate product detail. An overview of this database is described in the highlight article in this issue. These products were produced by the Multi-Resolution Land Characteristics (MRLC) Consortium–a group of 13 Federal programs in 10 agencies that partner to purchase Landsat imagery and create land cover products for the Nation. Products and imagery are Web-enabled for download from the MRLC website at www.mrlc.gov. The release of these NLCD 2001 products has been widely anticipated, and this updated information will support a wide variety of users, institutional sectors, and local- to national-scale applications.



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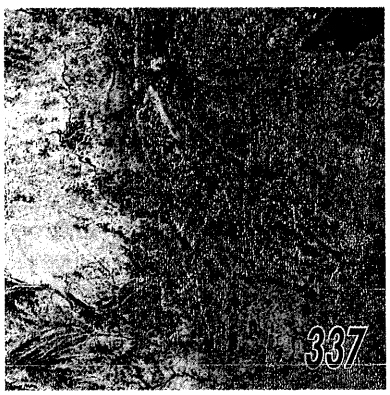

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Correction

In the November 2006 issue of *PE&RS*, the last name of an author was misspelled in the article "Evaluation of the Horizontal Resolution of SRTM Elevation Data" starting on page 1235. The correct spelling of the name is Josef Kellndorfer.

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