

# Canopy assessment of biochemical features by ground-based hyperspectral data for an invasive species, giant reed (*Arundo donax*)

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**Abstract** This study explored the potential use of hyperspectral data in the non-destructive assessment of chlorophyll, carbon, and nitrogen content of giant reed at the canopy level. We found that pseudoabsorption and derivatives of original hyperspectral data were able to describe the relationship between spectral data and measured biochemical characteristics. Based on correlogram analyses of ground-based hyperspectral data, we found that derivatives of pseudoabsorption were the best predictors of chlorophyll, carbon, and nitrogen content of giant reed canopies. Within the visible region, spectral data significantly correlated with chlorophyll

content at both 461 nm and 693 nm wavelengths. Within the near-infrared region, carbon levels correlated with hyperspectral data at five causal wavelengths: 1038 nm, 1945 nm, 1132 nm, 1525 nm, and 1704 nm. The best spectral wavelength for estimating nitrogen content was 1542 nm. Such relationships between nutrient content and spectral data were best represented by exponential functions in most situations.

**Keywords** Biological invasion · Chlorophyll content · Hyperspectral remote sensing · Imaging spectroscopy · Nitrogen content · Nutritional conditions

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## Introduction

Giant reed (*Arundo donax*) is a widely distributed invasive weed found throughout the southwestern US. This invasive plant can spread quickly and displace native vegetation, destroy wildlife habitats, and modify the physical and chemical characteristics of invaded areas (Bell et al. 1997; Decruyenaere and Holt 2005). Giant reed is found in a range of moist habitats including along roadsides, ditches, rivers, streams, and other wetlands. However, it appears that this species does not produce viable seed in North America, as seedlings have never been observed in the field. Thus *A. donax* expands exclusively through vegetative reproduction, either from underground rhizomes extending a colony or from plant fragments that are often spread further distances through

physical disturbances (Khudamrongsawat et al. 2004). It has been demonstrated that nutrient quality of vegetatively produced plants is important in understanding growth conditions and phenological patterns of *A. donax* in the field, and in the development of improved integrated management strategies for this and other invasive species (Cook 1985). Therefore, assessment of nutritional condition of these invasive plants may play an important role in predicting population growth and in estimating spread over large areas. The assessment of spatial variability of plant nutrition is important in assessing these factors over realistic landscapes due to changing biological and adaphic conditions that affect the invasive potential of *A. donax*. This is critical in developing the level of understanding necessary to enhance the efficacy of new management practices and to apply more precise control in invaded areas (Spencer et al. 2005). Therefore, it is expected that subtle spectral information from airborne hyperspectral data can eventually be used to quantitatively assess growth, development and potential spread of invasive *A. donax* over large landscapes, especially in areas that are inaccessible or hard to reach from the ground (Ge et al. 2006a, b).

Hyperspectral techniques have already been applied to estimate vegetative nutrient conditions, such as pigment content and nutrient levels of many plants (Chappelle et al. 1992; Blackburn 1998a, b). These techniques have then been used to develop a variety of hyperspectral-based vegetation indices have been subsequently used to estimate canopy biophysical components and the nutritional status of various plants (e.g. Peñuelas et al. 1994; Blackburn 1999). Hyperspectral data has also been used as a reliable tool to remotely assess vegetation condition at different temporal and spatial scales (Chappelle et al. 1992; Datt 1998; Blackburn and Steele 1999). The visible region of plant canopy spectral measurements is typically dominated by pigment absorptions; thus, narrow-band spectral data can potentially be used to estimate pigment contents and nutrient status at a canopy level, beyond a leaf level (Yoder and Pettigrew-Crosby 1995; Blackburn 1998a). Using near-infrared spectrometry (NIRS), concentrations of protein, amino acids, lignin, and cellulose can be estimated (Norris et al. 1976; Hunt et al. 1987; Card et al. 1988). Although predictive wavelengths are mostly obtained statistically, a few studies have demonstrated theoretical foundations based on causal

characteristics associated with spectral behaviors of specific elements such as the positions of photosynthetic pigments and nitrogen absorption (Curran 1989; Kokaly 2001).

The objectives of this study were: (1) to evaluate the capability of different transformed hyperspectral data (i.e., reflectance data ( $R$ ),  $\log(1/R)$ ) and their first and second derivatives to capture relationships between ground-based spectral data and three important nutrient components (i.e., chlorophyll, carbon, and nitrogen contents) at the plant canopy level; (2) to quantitatively determine relationships of the selected hyperspectral data with causal nutrient levels of *A. donax*, and (3) to select spectral-based variables relevant to the creation and evaluation of quantitative models to estimate these three nutritional contents at a canopy level.

## Methods

### Hyperspectral data collection and plant canopy nutritional characteristics

Our field study site (38° 41' 23"W, 121° 54' 47"N) was located in the Cache Creek Watershed, northeast of Woodland, California. This area is characterized by cool wet winters and hot dry summers. Temperatures range from slightly below freezing in the winter to more than 40°C in the summer. The native vegetation consists of oak woodlands, grasslands, mixed chaparral, and willow cotton stands in riparian areas. Agricultural and recreational use has caused vegetation changes within this watershed and many exotic plant species now exist in this area. Giant reed is just one of these invasive species, and it is a primary invader in and adjacent to riparian areas along Cache Creek. This invasion has resulted in serious ecological consequences and substantial economical damage in this area and many other areas within California.

Field samples were collected at test sites along Cache Creek in early July of 2002. Ten canopy areas were randomly chosen to obtain spectral measurements and leaf samples over a range of growth conditions. Spectral measurements were first made in situ and then the leaves were clipped from the canopy and returned to the laboratory where chlorophyll, carbon, and nitrogen levels were assessed. In order to collect spectral data from the upper tall

canopies (>10 m), we used a tall ladder to elevate the spectrometer to an adequate height to measure canopy reflectance. A FieldSpec@Pro FR spectrometer (Analytical Spectrum Devices (ASD) Inc., USA) was used to make all reflectance measurements, as it covers a spectral range of from 350 nm to 2500 nm, those wavelengths important for our nutritional components of interest. All reflectance measurements were taken between 10:00 am and 3:00 pm (Pacific Daylight Saving Time) at the nadir direction with a 25° field-of-view. For each canopy location, 10 random reflectance spectra were obtained, with each spectrum being an average from five scans. A white reference panel was used to normalize spectral reflectance measurements for each canopy to obtain standardized reflectance values. In all locations, the spectra were collected only under clear sky conditions (no observable cloud cover).

After the reflectance data were collected from each canopy, 6–12 leaf samples were obtained from each canopy for precise measurement of chlorophyll, carbon, and nitrogen contents of the scanned material. These leaf samples were taken from the upper, middle, and lower layers of the canopy and nutritional levels were obtained from the average values of the leaves sampled. To complete this assessment, a chlorophyll meter (SPAD-502, Minolta Co. Ltd., Japan) was used to measure the relative levels of the samples immediately after cutting. The samples were then taken to the USDA-ARS Aquatic Weeds analytical laboratory in Davis, California. The samples were first dried at 80°C for 48 h, and then ground to a fine powder using a Wiley Mill (Arthur H. Thomas Company, Philadelphia, PA). The carbon and nitrogen content of these dried leaf samples were directly measured using a Perkin-Elmer 2400 CHNS/O Analyzer, Series II (Perkin-Elmer, Boston, MA) with acetanilide used as the standard.

These canopy nutrient values were then used in correlation analysis through sequential regression with the values of different spectra and plotting the resulting coefficients of determination ( $r^2$ ) against the wavelengths to obtain the various correlograms. Because these canopy components are causally relevant to only a subset of the spectral data within a characteristic spectral region of the entire curve, the wavelengths used to develop these correlations for each nutritional component were confined to appropriate but different causal spectral region. That is,

spectral analyses regarding chlorophyll were only done within the visible region; the spectral data related to nitrogen components covered 1000–2000 nm while those related to carbon elements were located over the full spectral range examined (Curran 1989).

### Spectral data analysis

In the field, the canopy spectra were measured as reflectance values ( $R$ ), and were then transformed into pseudoabsorption values by logarithms of the reciprocal of reflectance ( $\log(1/R)$ ) (Blackburn 1998a). The first derivatives were also calculated from the differences of reflectance or pseudoabsorption values from two bands with a spectral distance of 2 nm, divided by the range of wavelengths (i.e.,  $\delta R$ , and  $\delta(\log(1/R))$ ). Statistical analysis was performed to select a subset of spectral data in order to develop the best-fit models using four types of basic mathematical models: linear, logarithmic, exponential, and power functions. The optimal wavelengths were selected from local maxima of the Coefficient of Determination for each compound within the spectral regions specified previously. Finally, hyperspectral data at those selected causal spectral positions were then used to develop estimation models on the basis of their statistical relationships with the spectral data. This assessment was conducted independently for each of the three nutrient compounds measured in this study.

## Results and discussion

### Canopy characteristics

There were a total of 79 leaf samples collected from the combined set of 10 selected canopy locations that were studied. Their statistical attributes (Table 1), show that at the leaf level, carbon content ranged from 41.44% to 48.36%, nitrogen content from 1.22% to 3.45%, and chlorophyll content from 23.70 to 45.50 (these are SPAD units of chlorophyll content rather than % content). At the canopy level, the corresponding values were obtained by averaging across the leaf samples for each location. Using these combined measures, the canopy values of carbon, nitrogen, and chlorophyll contents ranged from

**Table 1** Nutritional conditions of *Arundo donax* at both the leaf and canopy level

| Nutrient components | Leaf level  |                           | Canopy level |                           |
|---------------------|-------------|---------------------------|--------------|---------------------------|
|                     | Value range | Mean $\pm$ standard error | Value range  | Mean $\pm$ standard error |
| Carbon              | 41.44~48.36 | 44.40 $\pm$ 0.12          | 42.39~46.57  | 44.47 $\pm$ 0.33          |
| Nitrogen            | 1.22~3.45   | 2.47 $\pm$ 0.05           | 1.49~3.13    | 2.47 $\pm$ 0.12           |
| Chlorophyll         | 23.70~45.50 | 36.71 $\pm$ 0.55          | 27.88~40.31  | 36.33 $\pm$ 1.24          |

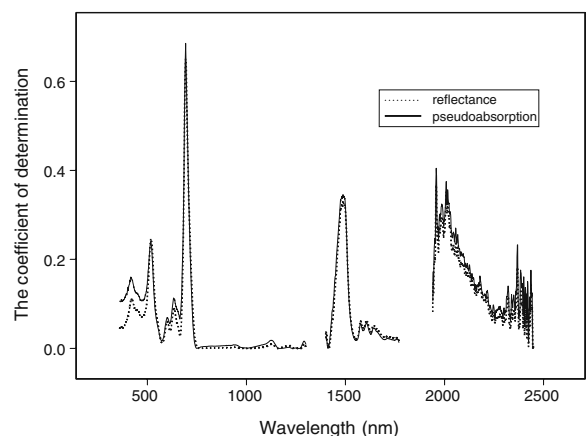
42.39% to 44.51%, 1.49% to 3.13%, and 27.88 to 40.31, respectively. This aggregation of leaf samples resulted in similar readings but a reduced range in all circumstances. At the canopy level, there was a strong positive correlation between carbon and nitrogen levels ( $r=0.86$ ), but the correlation between carbon and the measured amount of chlorophyll content was weak ( $r=0.30$ ). However, the correlation between nitrogen and chlorophyll content was somewhat stronger yielding a more moderate association ( $r=0.65$ ).

Although samples were obtained from only 10 canopy locations, such samples were reliable and sufficient to capture trends of measured nutrient values in association with the canopy level spectral data. Others have shown that from 5 to 15 samples may be required to show such correlations for spectral analysis between individual bands and related biochemical features in plants (Hruschka 1987). In a similar study on an invasive bracken fern, 12 sample sites were used to successfully quantify relationships between hyperspectral data and chlorophylls and carotenoids at the canopy level. This bracken study demonstrated that hyperspectral data at specific casual wavelengths was significantly correlated to chlorophyll and carotenoid contents (Blackburn and Steele 1999). Therefore, samples from 10 canopy locations used in this study were felt to be reasonable and thus sufficient to statistically determine the relationships between hyperspectral data and nutritional conditions for the ranges that we encountered in giant reed within our study sites. Further application in other areas is expected to require additional spectral assessments to ensure that these results are directly transferable to other times and locations.

#### Relationship of chlorophyll content with hyperspectral data

The four different forms of our mathematical models (linear, logarithmic, exponential, and power functions)

showed different relationships between nutritional conditions and the actual spectral data within the range of 400 nm to 2500 nm. Reflectance and pseudoabsorption had similar relationships with chlorophyll levels (Fig. 1). Reflectance and pseudoabsorption were well correlated with chlorophyll content at 693 nm (Table 2), where red absorption caused by chlorophyll pigmentation is known to be located. Therefore, the strength of such absorptions directly linked to chlorophyll content change in the leaves at each test site. The models with the best fits, were the logarithmic and linear functions, when used directly with measurements of reflectance and pseudoabsorption, respectively (Table 3). The use of hyperspectral-based derivatives improved these relationships with the highest correlation found between the chlorophyll content and the hyperspectral data at 461 nm (Table 2). This result implied that derivatives accentuated the blue absorption caused by carotenoids and led to a stronger correlation between spectral data and chlorophyll content. These derivatives were then used to estimate chlorophyll content (Table 3) with reasonable levels of fit ( $r^2$  from approximately 0.7 to 0.84).

**Fig. 1** Relationships between canopy chlorophyll content and reflectance data

**Table 2** Wavelength positions significantly correlated with chlorophyll content (coefficient of correlation >0.60,  $n=10$ ,  $\alpha=0.05$ )

|             | $R$                       | Log (1/ $R$ )             | $\delta R$ (nm)  | $\delta(\log [1/R])$   |
|-------------|---------------------------|---------------------------|--|--|
| Chlorophyll | <b>693*</b>               | <b>693</b>                | <b>461</b> , 767, 779                                    | <b>461</b> , 744   |
| Nitrogen    | 1957                      | 1957                      | <b>1016</b> , 1038, 1238, 1281, 1502, <b>1513</b> , 2009 | 1038, 1237, 1280, <b>1522</b> , 1584, 1619, 2009, 2257, 2401       |
| Carbon      | 1940–1985 ( <b>1945</b> ) | 1940–2000 ( <b>1945</b> ) | 951, <b>1038</b> , <b>1132</b> , 1518, 1704              | 649, 951, <b>1525</b> , <b>1704</b> , 2037, 2188, 2256, 2298, 2423 |

Note: \* Significant causal wavelengths, which were used to develop models of best-fit between spectral data and nutrient content in *Arundo donax*

Within the middle-infrared region (from 1300 nm to 2500 nm), strong relationships existed between hyperspectral data and chlorophyll content. For example, reflectance values at 1488 nm, 1960 nm, and 2015 nm were correlated with chlorophyll content. Such relationships were not caused directly by chlorophyll absorption as the spectral absorption patterns within this region derive primarily from nitrogen absorptions (Card et al. 1988; Curran 1989). Thus, in this study, underlying correlation between chlorophyll and nitrogen contents resulted in a strong correlation between chlorophyll content and the field collected spectral data.

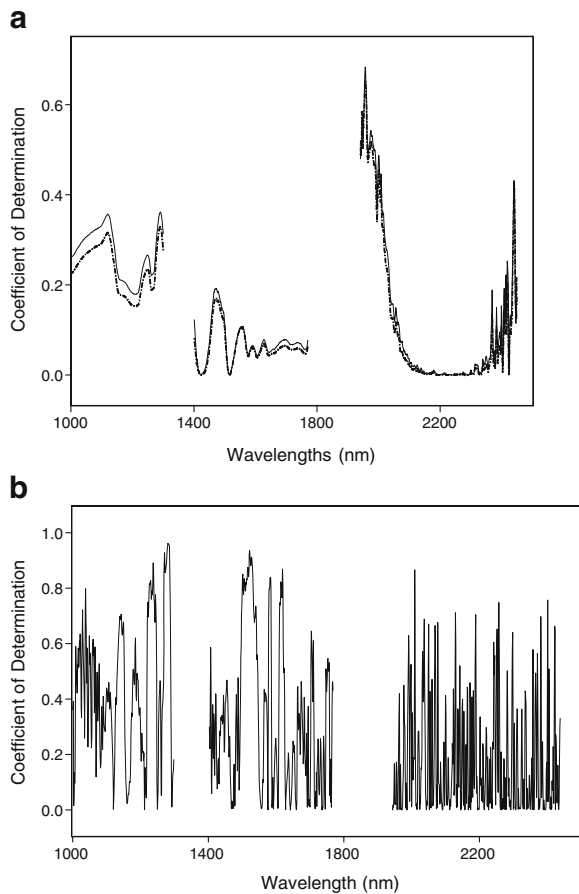
#### Relationship of nitrogen content with hyperspectral data

Within the visible and near-infrared regions of the spectrum, the measured hyperspectral reflectance data was highly correlated with nitrogen content at a few

specific spectral positions (Fig. 2a). In general, within the visible region of the spectra (350 to 680 nm) chlorophyll absorption dominates the spectral patterns that were observed. Therefore, correlations between nitrogen and spectral data within the visible region were believed to be caused by strong relationships between nitrogen and chlorophyll content, and the underlying wavelengths of nitrogen absorption at 1000 nm and above (Yoder and Pettigrew-Crosby 1995; Curran 1989; Kokaly 2001). Nitrogen absorptions primarily appeared within the middle-infrared region from 1000 nm to 2500 nm. Therefore, we focused our attention on the relationships between nitrogen content and spectral data within this casual spectral region. When developing correlograms between nitrogen content and the two types of spectral data (i.e.  $R$  and  $\log (1/R)$ ), the best correlation was found to occur around 1957 nm. This spectral position is actually very near the water and starch absorption positions but away from the nitrogen

**Table 3** Models of best-fit, spectral data types, and spectral positions of importance in estimating key biochemical components of *Arundo donax* canopy composition

| Biochemical attributes | Types of spectral data         | Causal band positions (nm) | Models                              | Coefficients of determination ( $R^2$ ) |
|------------------------|--------------------------------|----------------------------|-------------------------------------|---|
| Chlorophyll content    | Reflectance                    | 693                        | $87.80 + 51.87 \cdot \log(x)$       | 0.69                                    |
|                        | Pseudoabsorption               | 693                        | $87.08 - 22.53 \cdot x$             | 0.69                                    |
|                        | Derivative of reflectance      | 461                        | $159.30 \cdot \exp(-0.65 \cdot x)$  | 0.70                                    |
|                        | Derivative of pseudoabsorption | 461                        | $43.57 \cdot \exp(349.74 \cdot x)$  | 0.84                                    |
| Carbon content         | Reflectance                    | 1945                       | $40.23 \cdot \exp(2.19 \cdot x)$    | 0.68                                    |
|                        | Pseudoabsorption               | 1945                       | $61.59 \cdot \exp(-0.29 \cdot x)$   | 0.66                                    |
|                        | Derivative of reflectance      | 1038                       | $46.69 - 15573.01 \cdot x$          | 0.76                                    |
|                        | Derivative of reflectance      | 1132                       | $46.39 \cdot \exp(66.26 \cdot x)$   | 0.76                                    |
|                        | Derivative of pseudoabsorption | 1525                       | $49.08 \cdot \exp(46.36 \cdot x)$   | 0.77                                    |
|                        | Derivative of reflectance      | 1704                       | $48.34 \cdot \exp(-175.78 \cdot x)$ | 0.75                                    |
|                        | Derivative of pseudoabsorption | 1522                       | $4.99 \cdot \exp(333.99 \cdot x)$   | 0.92                                    |
| Nitrogen content       | Derivative of reflectance      | 1016                       | $4.46 \cdot \exp(-3141.22 \cdot x)$ | 0.83                                    |
|                        | Derivative of reflectance      | 1513                       | $4.13 \cdot \exp(-1378.94 \cdot x)$ | 0.84                                    |
|                        | Derivative of pseudoabsorption | 1522                       | $4.99 \cdot \exp(333.99 \cdot x)$   | 0.92                                    |



**Fig. 2** Relationships between nitrogen content and (a) reflectance data and (b) reflectance derivatives

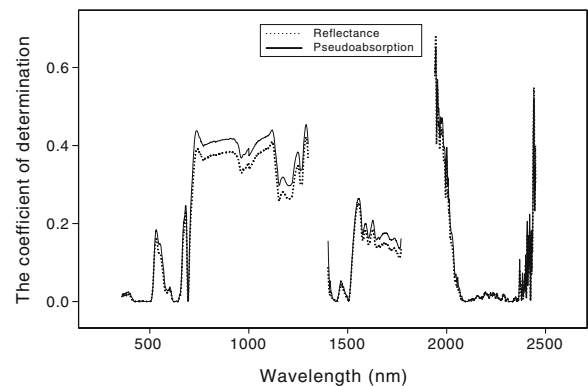
absorption position. Thus, no strong relationship was found between nitrogen content and the spectrum of either reflectance or pseudoabsorption within the near-infrared region.

Spectral derivatives did, however, improve the relationship between nitrogen levels and the spectral data overall (Fig. 2b). It was found that nitrogen content could be adequately estimated using spectral derivatives around three nitrogen absorption positions (Table 2). For example, the derivatives at 1016 nm, 1513 nm, and 1522 nm were highly correlated with nitrogen content as expected, since these wavelengths are found very close to normal nitrogen absorption peaks. On the other hand, the absorption peaks of carbon-containing materials such as starch and sugar had high correlations with nitrogen content. Therefore, around the carbon absorption positions of 1038 nm and 1704 nm (Curran 1989), the corresponding derivative-

based spectral data showed significant correlations with nitrogen content. Overall, the derivatives showed strong relationships with nitrogen content at three primary nitrogen absorption wavelengths (Table 2). These relationships were best described using exponential functions. The derivative of pseudoabsorption was the strongest determinant with respect to the empirical estimation of nitrogen content in the canopy (Table 3).

#### Relationship between carbon content and hyperspectral data

Within the visible region of the spectrum, reflectance and pseudoabsorption did not have strong relationships with canopy carbon content (Fig. 3). However, the carbon substrate showed a strong correlation with enhanced spectral data (e.g. the pseudoabsorption derivative) around 650 nm, although this wavelength is not known to have a causal relationship with carbon content. Within the near-infrared region, there was a significant correlation between reflectance and carbon content. This spectral pattern could attribute to canopy structures and the high reflectance from light scattering at cell wall interfaces (Kokaly 2001). In addition, due to the existence of multiple carbon-absorption bands, high correlation existed between carbon content and the hyperspectral data within the middle-infrared region of the spectra. Similarly, while using spectral derivatives, carbon contents were highly correlated with spectral data within the near-infrared and middle-infrared regions. These spectral derivatives were highly correlated with carbon con-



**Fig. 3** Relationships between carbon content and reflectance data

tent at five wavelength positions (Table 2). Other vegetation components, such as water and nitrogen, also have significant associations with carbon contents. These resulting relationships appeared around the underlying absorption positions of key canopy elemental components that are related to carbon substrates within the plant. For example, derivatives at 951 nm were related to water absorption, and at 1518 nm to nitrogen response. Although strong correlations existed between spectral data and carbon content at these wavelengths, they were not located near causal spectral positions related to overall carbon content. Therefore, based on this assessment, there were a total of five separate wavelengths available to develop estimation models of carbon levels (see Table 3).

## Conclusions

Hyperspectral data from canopies of giant reed were processed with different spectral formats, including both pseudoabsorption and derivative analysis. The correlations depended on the types of spectral data and the types of canopy nutritional components being assessed. Chlorophyll content of the *A. donax* canopies was highly correlated with spectral data at the 693 nm of visible red absorption. The nitrogen content correlated more effectively with hyperspectral derivatives at three causal nitrogen-absorption positions, 1016 nm, 1513 nm, and 1522 nm, respectively. For carbon content, the best correlations were located in the near- and middle- infrared regions, included 1038 nm, 1132 nm, 1525 nm, 1704 nm, and 1945 nm wavelength locations. In this study, comparisons on different types of spectral data demonstrated that the pseudoabsorption derivatives had the best correlations with the three canopy nutrients examined in this study. It was also found that they were located at key causal spectral positions and were best estimated by using exponential models.

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