Two new hyperspectral indices for comparing vegetation chlorophyll content

Amy E. FRAZIER\textsuperscript{a,b,1}, Le WANG\textsuperscript{a,b,*} and Jin CHEN\textsuperscript{c}

\textsuperscript{a}Department of Geography, University at Buffalo – The State University of New York, Buffalo, NY, USA; \textsuperscript{b}College of Resource Environment and Tourism, Capital Normal University, Beijing, China; \textsuperscript{c}State Key Laboratory for Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing, China

(Received 21 August 2013; final version received 17 December 2013)

The red edge region of a hyperspectral vegetation reflectance curve provides important information regarding the biochemical and biophysical parameters of plants such as stress, senescence, and chlorophyll capacity. However, shifts of the red edge position (REP) to longer or shorter wavelengths have also been correlated with other factors such as water content, nitrogen, and salinity. These other factors can confuse the effect of chlorophyll on REP. The objective of this study is to define two new hyperspectral curve indices, the red valley width (RVW) and the chlorophyll absorption region (CAR) that are designed to provide less-sensitive characterizations of the chlorophyll content of vegetation in order to allow better comparisons among spatially or temporally distant populations of vegetation. The RVW and the CAR are both located in the visible near-infrared portion of the light spectrum and are derived from multiple hyperspectral curve features that have been found to be correlated with chlorophyll content, thus making them less sensitive to other biophysical and biochemical factors that can affect the REP independently. The robustness of the two new features is tested using the Leaf Optical Properties Experiment database, and the findings are used to compare two populations of saltcedar (\textit{Tamarix} spp.) from a native habitat in China and an invasive habitat in the USA. Saltcedar is a highly invasive plant species in the USA but does not pose the same ecological and economic threats in its native habitat throughout Eurasia. The findings are interpreted in the context of the environmental characteristics of each region.

Keywords: remote sensing; spectral comparison; non-native; exotic species

1. Introduction

Saltcedar (\textit{Tamarix} spp.) is an exotic plant that was introduced to the southwestern USA in the mid-1800s and quickly became a dominant invader (1). It causes declines in ecological functioning along river systems (2–4) and an estimated $138 million in economic losses in the USA each year (5). However, these negative effects seen in the USA are in contrast to the environmental and economic benefits it provides in its native Eurasian habitat. In China, it is planted for windbreaks and sand fixation, provides a source of browse for sheep, goats, and cattle, and is even used as a cost-effective source of firewood in certain areas. The branches can be woven into baskets for household use or sold for income (6) and parts of the plant are often used to make a traditional Chinese medicine (7). Historically, saltcedar was rarely found growing in the wild in China (8), but because of these beneficial uses, it is currently being cultivated extensively in certain regions.

The discrepancies between the growth patterns of saltcedar in the USA and in China are confounding, and while considerable research has attempted to understand the mechanisms driving saltcedar’s spread in the USA, few studies have compared native and invasive plants, except Ref. (9). We hypothesize that there are differences in the biophysical and biochemical properties of saltcedar plants growing in a native vs. an invasive habitat, and we undertook a study to compare the chlorophyll content of plants from the two locations through hyperspectral vegetation reflectance measurements. Hyperspectral reflectance measurements provide a non-destructive method for studying the biophysical and biochemical composition of plants and have become a viable option for \textit{in situ} studies when laboratory testing is not feasible.

Considerable research has focused on identifying curve features within the visible and near-infrared (NIR) regions of the light spectrum that correlate to plant composition. In these regions, vegetation reflectance is highly influenced by the presence of leaf pigments, such as chlorophyll and carotenoids (10), and two parameters have been found to correlate well with plant composition. The first is the red edge (11), which refers to the abrupt ascending slope created by the chlorophyll absorption valley in the red region (12, 13). The red edge position (REP) is commonly defined as the maximum first derivative of this slope (i.e. the inflection point where the curve changes shape) (14–17). The second curve feature is the reflectance peak in the NIR region (680–750 nm). Both features have been found to provide important information regarding biochemical and biophysical parameters of plants such as stress, senescence, and chlorophyll capacity (18, 19).

*Corresponding author. Email: lewang@buffalo.edu

\textsuperscript{1}Presently at Department of Geography, Oklahoma State University, Stillwater, OK, USA
REP is highly influenced by chlorophyll content and will shift toward longer wavelengths as plant chlorophyll content increases (11, 18, 19). It is believed this shift occurs in response to a broadening of the chlorophyll absorption feature, which is centered around 680 nm (20, 21). Greater amounts of chlorophyll absorption in plants translate to a broader absorption feature, which essentially pushes the REP toward longer wavelengths. Many studies have utilized the correlation between REP and chlorophyll to study individual vegetation species (15, 16, 19, 22, 23). However, chlorophyll absorption is not the only factor affecting REP. It can be influenced by plant water content (11, 24, 25), nitrogen content (15, 26, 27), and salinity (28), as well as leaf scattering properties (11, 29). Specifically, Liu et al. (24) found that NIR reflectance increased as plant water content increased, and the higher amplitude of the NIR peak consequently drew the REP toward shorter wavelengths resulting in a non-chlorophyll-related shift in the REP. With field-based measurements, which are costly and time consuming to collect, it is impossible to determine from the curve alone whether the shift in REP is due to a decrease in chlorophyll content or an increase in plant water content. These additional factors make it difficult to compare the chlorophyll content of spatially distant populations of vegetation using REP because other biochemical and biophysical properties may be affecting its position.

Several other hyperspectral curve features have been correlated with chlorophyll content that are less sensitive to other parameters such as water content, nitrogen, or salinity because they are not located along the red edge. For example, the yellow edge position (YEP) is the point of maximum slope along the descending curve between the green reflectance peak and the chlorophyll absorption valley. The yellow edge is strongly related to reflectance in the green spectrum, and green reflectance has been used to measure leaf chlorophyll content (30), therefore YEP is also related to chlorophyll content. Additionally, two features within the chlorophyll absorption valley have been related to plant chlorophyll content (Figure 1). These features include the minimum reflectance ($R_0$) in the red valley (640–680 nm) and the corresponding wavelength position of $R_0$, defined as the red valley position (RVP) (17). These features have only been related to plant chlorophyll content and have not been linked to other biophysical and biochemical parameters. We hypothesize that by utilizing these additional features in conjunction with REP, we can develop less-sensitive chlorophyll prediction indices, which in turn can be used to compare the chlorophyll content of two healthy populations of saltcedar.

The objectives of this study are twofold. First, two new hyperspectral curve indices are introduced that are derived from multiple chlorophyll-related curve components. By designing the two new indices using a composite of REP with other features that also indicate chlorophyll but are less sensitive to non-chlorophyll biophysical and biochemical parameters, we hypothesize that they are better suited for comparing relative chlorophyll content between two spatially distant vegetation populations. The two new features include the red valley width (RVW) and the chlorophyll absorption region (CAR). Both features are described fully in Section 2.

The second objective is to compare the chlorophyll content of two populations of saltcedar from a native habitat in China and an invasive habitat in the USA. Due to the remote locations of these study sites, it has proven difficult to measure leaf chlorophyll content from field samples, particularly due to the lack of accessibility to laboratory testing facilities in China. Therefore, any type of comparison must be completed solely through hyperspectral reflectance measurements. If the two new features, RVW and CAR, prove to be robust at indicating chlorophyll content, they will be included along with the four other above-mentioned features to carry out a comprehensive comparison of the biophysical and biochemical composition of plants in the two habitats. The results are discussed in the environmental context of the study areas. This study is the first to undertake such a comparison between native and invasive saltcedar, and the results will help inform future comparisons of spatially distant vegetation populations.

2. Data and methods
2.1. Data

Ideally, this study would have collected chlorophyll measurements coincident with hyperspectral measurements for a broad range of vegetation types in a variety
of environments. However, the resources for undertaking a study of this magnitude were not available. Therefore, we utilized reflectance measurements and associated chlorophyll measurements from the Leaf Optical Properties Experiment database (LOPEX) to test the power of the two new features for predicting plant chlorophyll content. The LOPEX database was established in 1993 by the Joint Research Center Institute for Remote Sensing Applications in Ispra, Italy (31) and includes more than two thousand hyperspectral reflectance and transmittance measurements along with associated physical and biochemical parameters (e.g. chlorophyll, carotenoids, etc.) for leaf samples from more than 50 species of trees, crops, and plants. The data have been made publicly available for research purposes and have been used extensively in remote sensing to test curve correlations (14, 32, 33). This study utilizes hyperspectral and chlorophyll measurements from 44 samples of fresh leaves (dicotyledons). The 44 samples were divided into two groups for analysis: (i) woody, deciduous trees comprising 29 samples from 21 species and (ii) non-woody plants comprising 15 samples from 12 species (Table 1).

There are advantages and disadvantages to using the LOPEX database as opposed to targeted, species-specific field sampling. LOPEX allows for testing the chlorophyll correlations across a wide variety of vegetation types, including both woody and non-woody plants, thus allowing the results to be generalized. However, since saltcedar is not explicitly tested in the LOPEX database, only the generalized findings for non-woody vegetation can be used for a comparison. It is hoped that the results of this study will lead to additional, targeted studies assessing the species-specific performance of the new hyperspectral indices.

### Table 1. Woody and non-woody leaf samples analyzed.

| Woody, deciduous trees (# samples) | Non-woody plants (# samples) |
|-----------------------------------|-------------------------------|
| Alder (Alnus glutinosa)            | Alfalfa (Medicago sativa L.) (2) |
| Apricot (Armeniaca vulgaris) (2)   | Cabbage (Brassica oleracea L.)   |
| Ash (Fraxinus excelsior L.) (2)    | Clover (Trifolium pratense L.)   |
| Beech (Fagus sylvatica L.)        | Ivy (Hedera helix L.)           |
| Birch (Betula alba L.)            | Lettuce (Lactuca sativa)        |
| Chestnut (Castanea sativa) (2)    | Potato (Solanum tuberosum L.)   |
| Elm (Ulmus glabra)                | Soy (Soja hispida) (2)          |
| Fig (Ficus carica L.)             | Sugar Beet (Beta vulgaris L.)    |
| Hazel (Corylus avellana L.) (2)   | Sunflower (Helianthus annuus L.)|
| Linden (Tilia platyphyllos) (2)   | Tomato (Lycopersicum esculentum) |
| Maple (Acer pseudoplatanus L.) (2) | Vine-American (Vitis vinifera L.) |
| Mulberry (Morus nigra)            | Vine-white (Vitis vinifera L.)   |
| Oak (Quercus pubescens) (2)       | Wild vines (Vitis sivestris)     |
| Poplar (Populus canadensis)       |                               |
| Poplar (Populus tremula L.)       |                               |
| Cherry (Prunus serotina)          |                               |
| Acacia (Robinia pseudoacacia L.) (2) |                               |
| Red Oak (Quercus rubra)           |                               |
| Walnut (Juglans regia L.)         |                               |
| Willow (Salix alba L.)            |                               |

2.2. Defining the curve indices including RVW and CAR

Six indices were generated from the hyperspectral reflectance curves for each LOPEX sample including the four established indices REP, YEP, RVP, and \( R_0 \) and the two new indices RVW and CAR (Table 2). Since there are several accepted methods for determining the precise location of the REP, we first assessed the performance of four of the more common methods, which included the four-point interpolation method (34, 35), the linear extrapolation method described by Cho and Skidmore (26), fitting a higher order polynomial to the curve (36), and locating the position of the maximum first derivative between 670 and 737 nm (17). Ultimately we concluded that the maximum first derivative provided the most consistent REP positions for the purposes of comparison and so used only that method moving forward. Raw reflectance curves were smoothed using a 12-forward, 12-backward moving window prior to computing the first derivative to account for data artifacts and facilitate locating the REP. The YEP was also located by calculating the minimum first derivative along the smoothed curve in the region between the green peak and red valley (550–582 nm). RVP and \( R_0 \) were extracted from the raw curves following the methodologies in Gong et al. (17) and described in Table 2. Spectral data were processed using the Spectral Analysis and Management System (SAMs; University of California-Davis 2005).

Next, the two new indices, RVW and CAR, were generated from the hyperspectral reflectance curves. RVW is the difference in wavelength between REP and YEP and is computed by subtracting the YEP from REP. The theoretical foundation of the RVW is that increases
in plant chlorophyll content will broaden the chlorophyll absorption valley, thus shifting the REP toward longer wavelengths and the YEP toward shorter wavelengths. The RVW accounts for both of these shifts simultaneously and therefore minimizes adverse effects on REP from other parameters. CAR is an area-based measurement defined as the CAR. It is computed as the area of the polygon formed between the YEP and REP and encompassing all points along the hyperspectral curve. Therefore, it comprises four curve features that have been correlated with plant chlorophyll content: REP, YEP, RVP, and R0. The polygon is closed by connecting the YEP and REP with a straight line (Figure 2). CAR will increase as plant chlorophyll increases due to the broadening of the CAR in conjunction with the deepening of the chlorophyll absorption valley that has been found to be associated with higher chlorophyll concentration (37). By comparing the complete range of wavelengths across which chlorophyll is absorbed as well as the total area over which chlorophyll is absorbed, we hypothesize that these two new features will allow more accurate comparisons of vegetation populations with respect to chlorophyll content.  

All six curve features were regressed against chlorophyll a, chlorophyll b, and total chlorophyll measurements for their respective LOPEX sample to determine correlation coefficients. The correlation coefficients were then compared to the correlations of REP to determine the robustness of the two new curve features for serving as a proxy for leaf chlorophyll content.

### 2.3. Saltcedar comparison

For the second objective, we collected hyperspectral reflectance measurements for saltcedar plants from study sites in the USA and China. The US study site is located along the Forgotten River Reach (FRR) of the middle Rio Grande near the town of Candelaria, Texas (30.08°N, 104.42°W). Saltcedar has been established in the FRR for decades yet continues to displace native vegetation (38) and is therefore an ongoing concern for weed management. The study site in China is located near the aptly named Tamarisk River (TR), a tributary of the Yellow River, in Jingbian County, Shaanxi Province, north-central China (108.04°N, 37.45°W) (Figure 3). The climate in both study regions is semi-arid to arid, with maximum summer temperatures as high as 40 °C and average annual rainfall amounts of around 30–40 cm. *T. chinensis* is the dominant species of saltcedar found at both sites (9).  

Reflectance measurements were collected during the flowering period, which occurs in late March–early April in the FRR and mid-late July in the higher latitude TR site. Field campaigns were carried out during March 2006 for the FRR and July 2011 for the TR. Hyperspectral measurements were collected using portable, hand-held spectroradiometers (FRR: Analytical Spectral Device, Boulder, CO; TR: EKO Instruments, Co. MS-720, Tokyo, Japan). The instruments both have a 25° full angle cone of acceptance field of view and provide reflectance spectra at a spectral resolution of 10 nm in the ultraviolet/visible NIR range (350–1050 nm). While ideally the same type of spectrometer would have been used at both sites, it is not expected that the difference in manufacturer will have a significant effect on measurements since the specifications of each machine are similar.

---

### Table 2. Spectral features and a description of how they are derived.

| Feature Name | Description |
|--------------|-------------|
| REP          | Red edge position | Maximum value of the first derivative for wavelengths between 680 and 750 nm |
| YEP          | Yellow edge position | Maximum value of first derivative for wavelengths between 550 and 582 nm |
| R0           | Reflectance in red valley | Determined as the minimum reflectance within the region 640–680 nm |
| RVP          | Red valley position | Wavelength at position R0 |
| RVW          | Red valley width | Width of the chlorophyll absorption valley, determined as the difference between YEP and REP in wavelength |
| CAR          | Chlorophyll absorption region | Area of the polygon formed by points on the hyperspectral curve between the REP and YEP and completed by drawing a straight line between the REP and YEP |

---

Figure 2. Two new hyperspectral curve features: RVW and CAR.
Reflectance measurements of sub-canopy target plants were collected by pointing the fiber optic cable input vertically at breast height toward sun-illuminated branches. Each target was measured at least 10 times and measurements were averaged to reduce the effects from illumination variations, movement of branches by wind, and intrinsic noise from the sampling equipment. Care was taken to insure that the sky was nearly cloud free at the time of data acquisition, which in both locations occurred between 11:00 am and 2:00 pm local time. We sampled 13 targets in the FRR and 27 targets in the TR. Raw hyperspectral reflectance curves for several samples from each study site are shown in Figure 4. We used a standard t-test ($p$-value \(\leq 0.05\)) to compare the means of the targets from the two study sites to determine if there were statistically significant differences in the curve features. The differences are used to infer findings regarding the chlorophyll content of the two spatially distant populations of saltcedar and are discussed in the context of the two environments.

3. Results and discussion

3.1. RVW and CAR as indicators of chlorophyll content

The LOPEX analysis showed mixed results in terms of the correlation strength between chlorophyll and the two new indices, RVW and CAR, for the two groups of vegetation. RVW outperformed REP for both groups and generated higher correlation coefficients ($R^2$) in all cases (Table 3). These results indicate that RVW may be a better predictor of chlorophyll content than REP for both woody and non-woody plants, which is a significant finding and demonstrates the potential for a major innovation in the use of hyperspectral curve indices for chlorophyll assessment. Heretofore, the REP has been used almost singularly for correlating chlorophyll content to hyperspectral reflectance curves, but these results indicate RVW may be better suited for both woody and non-woody vegetation species. While further field and laboratory testing is needed to determine the strength of this correlation for specific species, this initial finding is promising.

The correlation results for CAR varied between the two groups of vegetation. For the woody species, $R^2$ values for CAR were much lower than either RVP or RVW (Figure 5) indicating poor correlations. However, $R^2$ values for the non-woody plants are very similar to those for both REP and CAR (Figure 6) indicating that CAR may have the potential to be used as a proxy for comparing chlorophyll content in non-woody vegetation populations. Once again, determining the robustness of CAR for specific species will require further field and laboratory testing.

| Curve features | Chlor. $a$ | Chlor. $b$ | Total chlor. |
|----------------|-----------|-----------|-------------|
| Woody species  |           |           |             |
| REP            | 0.249     | 0.183     | 0.234       |
| RVW            | 0.256     | 0.211     | 0.249       |
| CAR            | 0.045     | 0.027     | 0.041       |
| Non-woody species |         |           |             |
| REP            | 0.357     | 0.360     | 0.378       |
| RVW            | 0.378     | 0.392     | 0.386       |
| CAR            | 0.337     | 0.308     | 0.334       |

Figure 3. Study site locations for the FRR of the Rio Grande located in southwestern Texas, USA (top), and the TR located in Shaanxi Province, China (bottom).

Figure 4. Raw hyperspectral reflectance curves for saltcedar targets from the US and China study sites.
laboratory testing. However, since saltcedar is a non-woody plant and CAR performed comparably to RVP and RVW for this type of vegetation, the second objective will be carried out using both RVW and CAR. The overall findings from LOPEX analysis are promising because they indicate that the two new indices are an innovative means of deriving chlorophyll content from hyperspectral reflectance curves.
3.2. Saltcedar comparison

Based on the promising results from the LOPEX analysis, the comparison between the native and non-native populations of saltcedar was carried out using all six hyperspectral indices (i.e. the four established indices and the two new indices). The t-test results indicate there is a significant difference ($p \leq 0.02$) in the location of the REP for the two populations (Table 4). The REP for the China plants is shifted to the right, toward longer wavelengths, and the REP for the US population is shifted to the left, toward shorter wavelengths. Since we measured two healthy populations of saltcedar that did not show any signs of disease or senescence, we did not expect large differences in REP, however even the small difference of 1.71 nm between the mean REP locations was found to be significant. The location and depth of the red valley, RVP and $R_0$, respectively, were also both significant ($p \leq 0.05$) between the two populations. The location of YEP was not statistically significant between the two populations.

Based only on the above information, it would be rational to conclude that the plants sampled in China contain a greater amount of chlorophyll than the plants sampled in the USA because REP is shifted significantly toward longer wavelengths (indicating a broader range of chlorophyll absorption), and the reflectance at the RVP is significantly lower (indicating a deeper chlorophyll absorption valley). However, the two new curve features indicate a much different conclusion. Neither RVW nor CAR showed significant differences between the two populations (Table 4). Since RVW outperformed REP in the LOPEX analysis, and CAR is comprised of three features (REP, $R_0$, and RVP) that were found to be significant independently, the RVW and CAR findings suggest that other factors may be influencing those indices such as nitrogen content, water content, or salinity. This alternative conclusion is actually more reasonable, particularly when explained in the context of the environmental conditions at each study site.

3.3. Environmental context

Nitrogen (N) is a necessary component for the formation of chlorophyll in plants, and plant nitrogen status is often related to chlorophyll content (29, 39). N content likewise affects REP with higher N content shifting the REP toward longer wavelengths (27, 40). We were unable to measure N directly during field campaigns nor through the LOPEX data-set, but we did observe saltcedar growing in close proximity to agricultural lands in the China study site. In several cases, saltcedar was growing amongst crops and was also planted deliberately as a row crop in certain areas. These observations suggest that the plants in China are receiving N directly through fertilizer treatments or indirectly through run-off. In contrast, the US site is remote from human settlements and agricultural areas making it unlikely that the plants receive N treatments. We also observed a double-peak feature in some of the first derivative spectra from the China plants (although all REPs fell within the second peak) but did not find a double peak in any of the US samples. The double peak is commonly referred in studies examining N content (26) and provides further evidence that there is an increase in N for the China samples that may be causing a non-chlorophyll-related shift in REP.

Differences in water content between the two environments may also be causing non-chlorophyll-related shifts in REP. Higher plant water content has been found to increase NIR reflectance, thus drawing the REP toward shorter wavelengths (24). Without field measurements, it is difficult to draw formal conclusions due to variations in growing season, annual temperature, precipitation, and sampling times between the two countries. However, our field-based observations indicate that the US plants likely receive more water than the plants in China and therefore may have higher water content. Saltcedar is heavily dependent on abundant water supplies, and seeds require complete saturation during the early weeks of germination (41, 42). The US site is located on the Rio Grande where there are typically adequate water supplies through the spring and summer. In contrast, the China site comprises a former lake bed that has been dry for approximately 10 years. These perceived differences in water supply may be causing REP to shift toward shorter wavelengths in the US samples. The two new hyperspectral indices we introduced are less sensitive to water content, which may explain their lack of significance.

Salinity is a third possible explanation for non-chlorophyll-related shifts in REP between the two sites. Increased salinity has been found to cause in increase in REP for certain species (28) but should not impact RVW or CAR. Saltcedar is extremely salt tolerant (42, 43) and will draw salt up from the soil and excrete it through the leaves. Saltcedar is frequently planted in China to desalinate potential agricultural land, and while we did not measure salinity directly, a salt crust was observed on the soil in the China site, providing evidence of high soil salinity. An increase in salinity would be yet a third, non-chlorophyll-related factor causing an increase in the REP for the China samples. It should be noted that not all studies have found a relationship between species’ REP and salinity (44, 45). Therefore, correlations should be tested specifically for saltcedar before any firm

| Feature | US (Mean) | China (Mean) | $p$-value |
|---------|-----------|--------------|-----------|
| REP     | 722.00    | 723.71       | 0.0147**  |
| YEP     | 570.75    | 571.14       | 0.1722    |
| $R_0$   | 0.1212    | 0.0632       | 0.0493*   |
| RVP     | 672.50    | 673.57       | 0.0539*   |
| RVW     | 151.50    | 152.57       | 0.0577    |
| CAR     | 18.63     | 11.50        | 0.0989    |

*Significant at 0.95 confidence level.
**Significant at 0.98 confidence level.
conclusions can be made. Future work will focus on collecting field measurements of chlorophyll, nitrogen, water content, and salinity for saltcedar plants in order to test and validate the two new curve features we propose in this study.

4. Conclusions

In this paper, we define two new hyperspectral curve features, the RVW and the CAR, that are designed to provide a less-sensitive indication of the relative chlorophyll content of vegetation by minimizing the effects of other biophysical and biochemical parameters. REP has been found to be highly correlated with leaf chlorophyll content, but it is also influenced by other factors including nitrogen, water content, and salinity. The innovation of this study is the development of RVW and CAR, which are less sensitive to these other factors, and therefore may provide a better means for assessing the chlorophyll content of vegetation. We tested these features using the LOPEX database and found that RVW was better correlated with plant chlorophyll content than REP for both woody and non-woody species. CAR performed similarly as well as REP for assessing chlorophyll content in non-woody species. We used these new spectral indices in a comparison of saltcedar plants from a native habitat in China and an invasive habitat in the USA. Our findings indicate that while REP and other unconstrained curve features were statistically significant between the two populations, RVW and CAR did not show significant differences. These results suggest that the shift in the REP toward longer wavelengths in the China samples may be due to non-chlorophyll-related factors such as nitrogen, water content, or salinity. Since there is no other method that allows comparison of chlorophyll content without lab sampling, these two new features may provide more robust means for carrying out such studies and deserve rigorous testing through field and lab sampling.

The study is not without limitations. The inability to actually sample the chlorophyll content for the two populations of saltcedar hinders our ability to validate the species-level performance of the two new indices. While the differing environmental site conditions can be used to explain the results, in the future, we intend to perform more rigorous sampling to validate these indices across a wide variety of plant types using our own laboratory and field data.

Acknowledgements

This study was partially supported by grants to Le Wang from the National Science Foundation (NSF) (DEB-0810933 and BCS-0822489), the US Department of Agriculture CSREES Award 2004-38899-02181, and the Open Research Development Fund, State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University. The study was also partially supported by grants to Amy Frazier from the NSF Integrative Graduate Education and Research Traineeship (IGERT) in Geographic Information Science (DGE-0333417) and the University at Buffalo, Mark Diamond Research Foundation (SU-1107).

Notes on contributors

Amy E. Frazier is an assistant professor of Geography at Oklahoma State University. Her research centers on the use of remote sensing and landscape ecology to model landscape patterns and processes.

Le Wang is an associate professor at the University at Buffalo. His research interests are in remote sensing and its application in environmental science and urban study.

Jin Chen is a professor at Beijing Normal University. His research interest lies in remote sensing and land use and land cover change.

References

(1) Reynolds, L.V.; Cooper, D.J. Environmental Tolerance of an Invasive Riparian Tree and Its Potential for Continued Spread in the Southwestern US. J. Veg. Sci. 2010, 21, 733–743.
(2) Engle-Wilson, R.; Ohmart, R. Floral and Attendant Faunal Changes on the Lower Rio Grande between Fort Quitman and Presidio, TX. Proceedings of the National Symposium on Strategies for Protection and Management of Floodplain Wetlands and Other Riparian Ecosystems, U.S. Forest Service, General Technical Report WO-12. U.S. Department of Agriculture, Forest Service: Vancouver, 1978; pp 139–147.
(3) Hunter, W.; Ohmart, R.; Anderson, B. Use of Exotic Saltcedar (Tamarix chinensis) by Birds in Arid Riparian Systems. Condor 1988, 90, 113–123.
(4) Glenn, E.P.; Nagler, P.L. Comparative Ecophysiology of Tamarix ramosissima and Native Trees in Western U.S. Riparian Zones. J. Arid Environ. 2005, 61, 419–446.
(5) Zavaleta, E. The Economic Value of Controlling and Invasive Shrub. Ambio 2000, 29, 462–467.
(6) Zhu, Y.; Xu, P. Tamarix and Its Value of Expansion (in Chinese). Forestry of Shaxi 2001, 6, 22.
(7) Huang, S.; Liang, J. Progress of Studies on Tamarix Linn. Strait Pharm. J. 2007, 19, 5–9.
(8) Forbes, F.B.; Hemsley, W.B. An Enumeration of All of the Plants Known from China Proper, Formosa, Hainan, Corea, the Luchu Archipelago, and the Islands of Hong-kong, Together with their Distribution and Synonymy. J. Linnean Soc. Bot. 1887, 23 (153–154), 241–348.
(9) Gaskin, J.M.; Schaal, B.A. Hybrid Tamarix Widespread in US Invasion and Undetected in Native Asian Range. Proc. Nat. Acad. Sci. 2002, 99 (17), 11256–11259.
(10) Jensen, J.R. Remote Sensing of the Environment: An Earth Resource Perspective; Prentice Hall: Upper Saddle River, NJ, 2000.
(11) Horler, D.N.H. The Red Edge of Plant Leaf Reflectance. Int. J. Remote Sens. 1983, 4 (2), 273–288.
(12) Gausman, H.W. Reflectance of Leaf Components. Remote Sens. Environ. 1977, 20, 183–193.
(13) Curran, P.J. Remote Sensing of Foliar Chemistry. Remote Sens. Environ. 1989, 30, 271–278.
(14) Baranoski, G.V.G.; Rokne, J.G. A Practical Approach for Estimating the Red Edge Position of Plant Leaf Reflectance. Int. J. Remote Sens. 2005, 26 (3), 503–521.
(15) Chang-Hua, J.U.; Tian, Y.; Yao, X.; Cao, W.; Zhu, Y.; Hannaway, D. Estimating Leaf Chlorophyll Content Using Red Edge Parameters. Pedosphere 2010, 20 (5), 633–644.
(16) Filella, I.; Penuelas, J. The Red Edge Position and Shape as Indicators of Plant Chlorophyll Content, Biomass and Hydric Status. *Int. J. Remote Sens.* **1994**, *15* (7), 1459–1470.

(17) Gong, P.; Pu, R.; Heald, R.C. Analysis of in Situ Hyperspectral Data for Nutrient Estimation of Giant Sequoia. *Int. J. Remote Sens.* **2002**, *23* (9), 1827–1850.

(18) Collins, W. Remote Sensing of Crop Type and Maturity. *Photogramm Eng. Rem. S.* **1978**, *44* (1), 43–55.

(19) Curran, P.J.; Dungan, J.L.; Gholz, H.L. Exploring the Relationship between Reflectance Red Edge and Chlorophyll Concentration in Slash Pine Leaves. *Tree Physiol.* **1995**, *7*, 33–48.

(20) Buschmann, C.; Nagel, E. *In vivo* Spectroscopy and Internal Optics of Leaves as Basis for Remote Sensing of Vegetation. *Int. J. Remote Sens.* **1993**, *14*, 711–722.

(21) Dawson, T.P.; Curran, P.J. Technical Note A New Technique for Interpolating the Reflectance Red Edge Position. *Int. J. Remote Sens.* **1998**, *19* (11), 2133–2139.

(22) Gitelson, A.A.; Merzlyak, M.N.; Lichtenthaler, H.K. Detection of Red Edge Position and Chlorophyll Content by Reflectance Measurements near 700 nm. *J. Plant Physiol.* **1996**, *148*, 501–508.

(23) Pinar, A.; Curran, P.J. Technical Note Grass Chlorophyll and the Reflectance Red Edge. *Int. J. Remote Sens.* **1996**, *17*, 351–357.

(24) Liu, L.; Wang, J.; Huang, W.; Zhao, C.; Zhang, B.; Tong, Q. Estimating Winter Wheat Plant Water Content Using Red Edge Parameters. *Int. J. Remote Sens.* **2004**, *25* (17), 3331–3342.

(25) Peñuelas, J.; Filella, I.; Biel, C.; Serrano, L.; Savé, R. The Reflectance at the 950–970 nm Region as an Indicator of Plant Water Status. *Int. J. Remote Sens.* **1993**, *14* (10), 1887–1905.

(26) Cho, M.A.; Skidmore, A.K. A New Technique for Extracting the Red Edge Position from Hyperspectral Data: The Linear Extrapolation Method. *Remote Sens. Environ.* **2006**, *101*, 181–193.

(27) Mutanga, O.; Skidmore, A.K. Red Edge Shift and Biochemical Content in Grass Canopies. *ISPRS J. Photogramm. Rem. S.* **2007**, *62*, 34–42.

(28) Poss, J.A.; Russell, W.B.; Bonos, S.A.; Grieve, C.M. Salt Tolerance and Canopy Reflectance of Kentucky Bluegrass Cultivars. *HorticScience* **2010**, *45* (6), 952–960.

(29) Boocbs, F.; Kupfer, G.; Dockter, K.; Kühbaurh, W. Shape of the Red Edge as Vitality Indicator for Plants. *Int. J. Remote Sens.* **1990**, *11*, 1741–1753.

(30) Feng, Y.; Miller, J.R. Vegetation Green Reflectance at High Spectral Resolution as a Measure of Leaf Chlorophyll Content. *Proceedings of the 14th Canadian Symposium on Remote Sensing*, Calgary, Alberta, May 6–10 1991; pp 351–355.

(31) Hosgood, B.; Jacquemoud, S.; Andriolo, G.; Verdebout, J.; Pedrini, A.; Schmuck, G. Leaf Optical Properties Experiment 93 (LOPEX93). Report EUR 16095 EN; European Commission, Joint Research Centre, Institute for Remote Sensing Applications: Ispra, Italy, 2005.

(32) Wang, L.L.; Hunt, E.R.; Qu, J.J.; Hao, X.J.; Daughtry, C.S.T. Estimating Dry Matter Content of Fresh Leaves from the Residuals between Leaf and Water Reflectance. *Remote Sens. Lett.* **2011**, *2*, 137–145.

(33) Wu, J.J.; Zhang, J.; Lü, A.F.; Zhou, L. An Exploratory Analysis of Spectral Indices to Estimate Vegetation Water Content Using Sensitivity Function. *Remote Sens. Lett.* **2012**, *3*, 161–169.

(34) Danson, F.M.; Plummer, S.E. Red-Edge Response to Forest Leaf Area Index. *Int. J. Remote Sens.* **1995**, *16*, 183–188.

(35) Guyot, G.; Baret, F.; Jacquemond, S. Imaging Spectroscopy for Vegetation Studies. In *Imaging Spectroscopy: Fundamentals and Prospective Application*; Toselli, F. and Bodechtel, J., Eds.; Kluwer: Dordrecht, 1992; pp 145–165.

(36) Pu, R.L.; Gong, P.; Tian, Y.; Miao, X.; Carruthers, R.I.; Anderson, G.L. Using Classification and NDVI Differentiating Methods for Monitoring Sparse Vegetation Coverage: A Case Study of Saltcedar in Nevada, USA. *Int. J. Remote Sens.* **2008**, *29*, 3987–4011.

(37) Kokaly, R.F.; Despain, D.G.; Clark, R.N.; Livo, K.E. Mapping Vegetation in Yellowstone National Park Using Spectral Feature Analysis of AVIRIS Data. *Remote Sens. Environ.* **2003**, *84*, 437–456.

(38) Frazier, A.E.; Wang, L. Characterizing Spatial Patterns of Invasive Species Using Sub-pixel Classifications. *Remote Sens. Environ.* **2011**, *115*, 1997–2007.

(39) Everitt, J.F.; Richardson, A.J.; Gausman, H.W. Leaf Reflectance–Chlorophyll Relations in Buffelgrass. *Photogramm. Eng. Rem. S.* **1985**, *51*, 463–466.

(40) Lamb, D.W.; Steyn-Ross, M.; Schiare, P.; Hanna, M.M.; Silvester, W.; Steyn-Ross, A. Estimating Leaf Nitrogen Concentration in Ryegrass (*Lolium* spp.) Pasture Using the Chlorophyll Red-edge: Theoretical Modelling and Experimental Observations. *Int. J. Remote Sens.* **2002**, *23* (18), 3619–3648.

(41) DiTomasso, J.M. Impact, Biology, and Ecology of Saltcedar (*Tamarix* spp.) in the Southwestern United States. *Weed Technol.* **1998**, *12* (2), 326–336.

(42) Everitt, B. Ecology of Saltcedar – A Plea for Research. *Environ. Geol.* **1980**, *3*, 77–84.

(43) Busch, D.E.; Smith, S.D. Mechanisms Associated with Decline of Woody Species in Riparian Ecosystems of the Southwestern U.S. *Ecol. Monogr.* **1995**, *65*, 347–370.

(44) Leone, A.P.; Menenti, M.; Buondonno, A.; Letizia, A.; Maffei, C. G. Sorrentino. A Field Experiment on Spectrometry of Crop Response to Soil Salinity. *Agric. Water Manage.* **2007**, *89*, 39–48.

(45) Zhang, T.T.; Zeng, S.L.; Gao, Y.; Ouyang, Z.T.; Li, B.; Fang, C.; Zhao, B. Using Hyperspectral Vegetation Indices as a Proxy to Monitor Soil Salinity. *Ecol. Indic.* **2011**, *11*, 1552–1562.