

Remote Sensing of Invasive Leafy Spurge using Reflectance and Imaging Spectroscopy

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Abstract

Leafy spurge (*Euphorbia esula* L.) is a noxious invasive weed that infests over 1.2 million hectares of land in North America. One of the fundamental needs in leafy spurge management is cost-effective, large-scale, and long-term monitoring of plant populations. Leafy spurge has distinctive yellow-green flower bracts which are spectrally unique when compared to co-occurring green vegetation; the spectral signature is caused by a reduction of chlorophyll allowing various carotenoids to influence the reflectance spectrum. In 1999, Airborne Visible-Infrared Imaging Spectrometer (AVIRIS) data were acquired over Devils Tower National Monument in Northeastern Wyoming. Accuracy of Spectral Angle Mapper classification for flowering leafy spurge was highest using a threshold of 3.5° , which is consistent with both reflectance spectroscopy data and simulations using a canopy radiative transfer model. The minimum detectable cover of flower bracts is about 10%, which is about 35% total cover of leafy spurge, and is ideal for biological control with flea beetles (*Aphthona* spp.).

Introduction

Detection of invasive weeds is the first step for management and remote sensing promises more complete maps over larger areas at lower cost than ground surveys (Everitt et al., 1995b, 2002). The more general problem is detecting individual plant species amongst other vegetation, because the reflectance spectrum of green leaves is based on pigment concentrations, cellular structure, and water (Gates et al., 1965; Knipling, 1970).

Plant species that can be remotely sensed have qualitative or quantitative spectral differences that are distinctive at some stage of their phenology. As shown in Fig. 1, leafy spurge (*Euphorbia esula* L.) has bright yellow-green flower bracts, which are detectable by remote sensing starting with aerial photography (Everitt et al., 1995a; Anderson et al., 1996; O'Neill et al., 2000; Parker Williams and Hunt, 2002, 2004; Dudek et al., 2004; Glenn et al., 2005; Casady et al., 2005; Lawrence et al., 2006; Mladinich et al., 2006; Hunt et al., 2006, 2007; Mitchell and Glenn, 2009a, 2009b). The yellow-green color of the flower bracts is due to an 86% reduction of chlorophylls a and b, and a 64% reduction of carotenoids (Table 1).

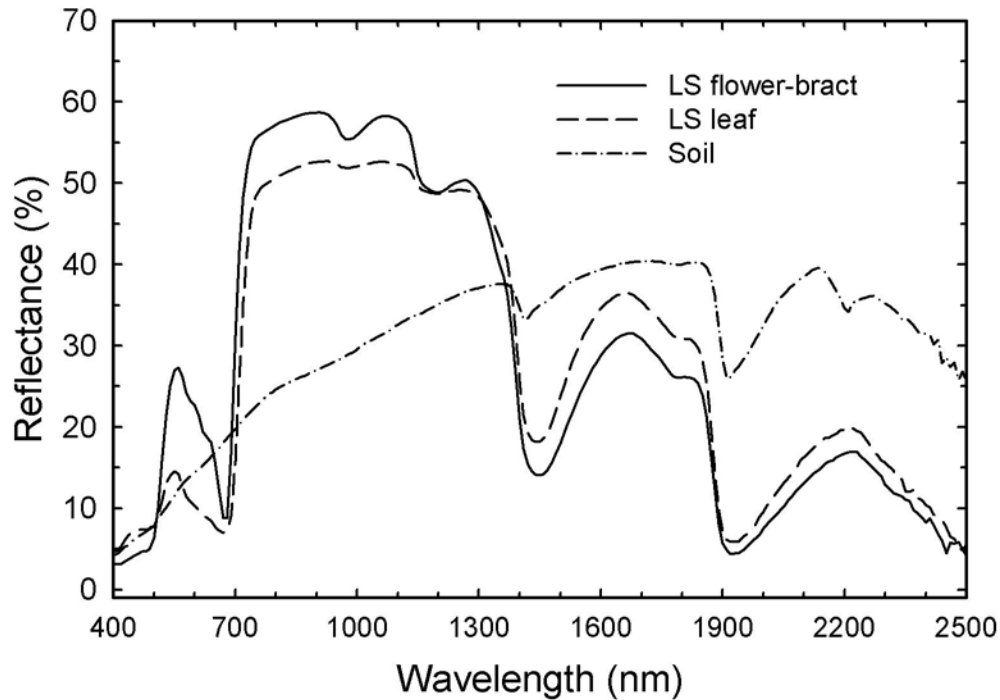


Figure 1. Spectral reflectances of flower-bracts and leaves of leafy spurge (LS) along with a bright, dry soil, obtained using an ASD FieldSpec Pro FR spectroradiometer. Data were acquired using an ASD Fieldspec Pro FR spectrometer attached to a Li-Cor integrating sphere (Hunt et al., 2004).

Table 1. Pigment concentrations of leaves and flower of leafy spurge. Data are mean and standard error (N = 10). Data from Hunt et al. (2004).

	Chlorophyll a	Chlorophyll b	Carotenoids	Car:Chl
----- $\mu\text{g g}^{-1}$ fresh weight -----				
Flower-bracts	61.5 \pm 4.0	19.8 \pm 2.0	77.1 \pm 2.3	0.96 \pm 0.09
Leaves	387.6 \pm 11.4	109.9 \pm 5.2	138.0 \pm 4.4	0.28 \pm 0.03

Using mixture-tuned matched filtering with Airborne Visible InfraRed Imaging Spectrometer (AVIRIS) data, Parker Williams & Hunt (2002, 2004) found that flowering leafy spurge can be detected with up to 95% overall accuracy. However, other studies found lower

overall accuracies using mixture-tuned matched filtering (Dudek et al., 2004; Glenn et al., 2005; Mitchell and Glenn, 2009a,b). Some of the differences may be attributed to the environmental context of the different locations (Andrew and Ustin, 2008).

Other invasive species are also detectable using hyperspectral remote sensing (Lass et al., 2002, 2005; Underwood et al., 2003; Ustin et al., 2004; Mundt et al., 2005; Andrew and Ustin, 2008). For species not yet studied, it is inefficient and expensive to assess the detection potential with remote sensing simply by acquiring and field checking imagery. Leaf spectral reflectances and transmittances can be used with canopy radiative transfer models (Verhoef, 1984; Goel 1988) to make predictions of what, where and when a particular plant species may be detected.

A classification method used frequently with imaging spectrometer data is the Spectral Angle Mapper (Kruse et al., 1993). Because calculation of the spectral angle does not rely on image statistics, as does mixture-tuned matched filtering, it is a good choice for analyzing spectral differences with both reflectance and imaging spectroscopy (Price, 1994; Cochrane, 2000). This study uses spectral angles with measured and simulated canopy reflectances to determine the effect of reference and target variability with respect to the cover of flowering leafy spurge. Assessment of similarity using spectral angles on canopy model output could provide a methodology to predict which invasive species may be determined by remote sensing.

Methods

Spectral Angle Mapper

Kruse et al. (1993) defined the spectral angle between two reflectance spectra based on vector algebra:

$$\Theta = \arccos [\mathbf{R} \cdot \mathbf{T} / (\|\mathbf{R}\| \|\mathbf{T}\|)] \quad [1]$$

where Θ is the spectral angle in radians or degrees, the vector \mathbf{R} is a reference spectrum, and the vector \mathbf{T} is the target or test spectrum. The numerator is the dot product of vectors \mathbf{R} and \mathbf{T} , which is calculated:

$$\mathbf{R} \cdot \mathbf{T} = R_{\lambda_1}T_{\lambda_1} + R_{\lambda_2}T_{\lambda_2} + \dots + R_{\lambda_n}T_{\lambda_n} \quad [2]$$

where R is the reflectance of the reference spectrum and T is the reflectance of the target spectrum for n number wavelengths or bands from λ_1 to λ_n . The denominator in Eq. 1 is the product of the normalized vectors \mathbf{R} and \mathbf{T} , where normalization of the reference spectrum is defined:

$$\|\mathbf{R}\| = (R_{\lambda_1}^2 + R_{\lambda_2}^2 + \dots + R_{\lambda_n}^2)^{0.5} \quad [3]$$

and $\|\mathbf{T}\|$ is defined similarly. Θ can be determined for any two spectra, whether from field portable spectrometers, multispectral sensors, or imaging spectrometers.

The Spectral Angle Mapper (Kruse et al., 1993) classification technique calculates Θ for each pixel (target) in an image using a reference spectrum. A threshold value of Θ is selected so that pixel Θ less than or equal to the threshold is classified as a match to the reference spectrum and pixel Θ greater than the threshold is classified as a non-match. A low threshold will increase the number of false negatives (errors of omission) and lower the producer accuracy, whereas a high threshold will increase the number of false positives (errors of commission) and lower the user accuracy.

Study Area

The original study was conducted as part of The Ecological Area-wide Management of (TEAM) Leafy Spurge project (Anderson et al., 2003). The study site was around Devils Tower National Monument in Northeastern Wyoming (Fig. 2), between 44.4° to 44.6° North latitude and 104.6° to 104.9° West longitude (Parker Williams and Hunt, 2002, 2004). The vegetation in the study area is a mosaic of conifer woodlands, northern mixed-grass prairie, and riparian zones with deciduous shrubs and trees. Leafy spurge was well established throughout the study area (Parker Williams and Hunt, 2002).

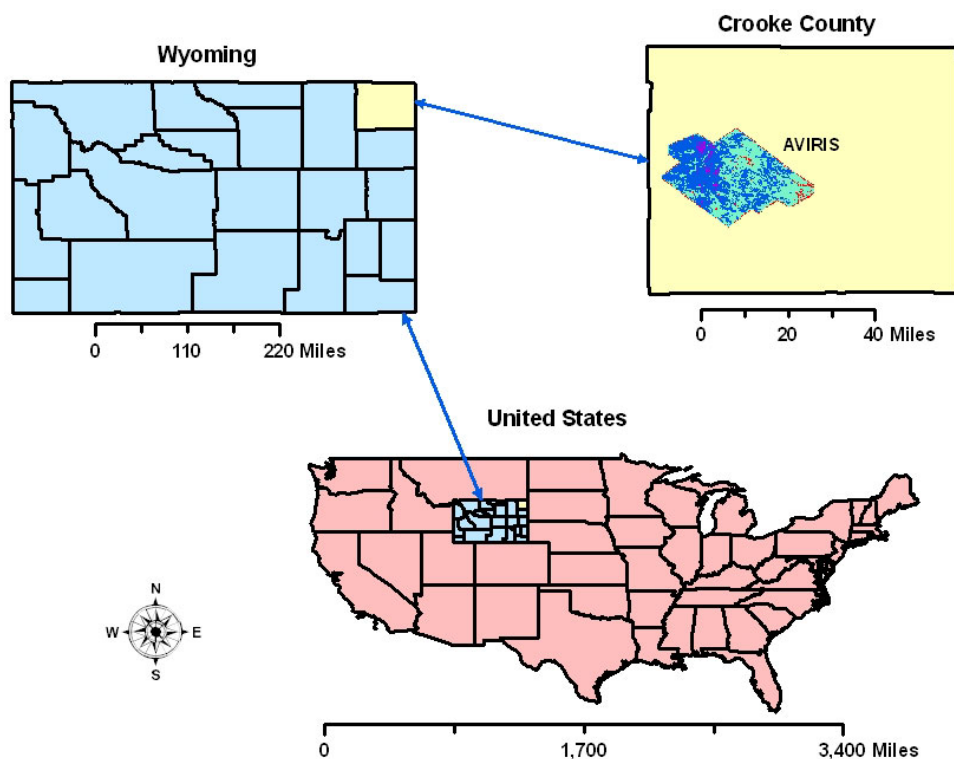


Figure 2. Location of study area and the Airborne Visible Infrared Imaging Spectrometer (AVIRIS) flightlines. Devils Tower National Monument is in the north-eastern section of the AVIRIS imagery.

The period of flowering in 1999 began in early June and lasted until mid July. All of the ground data collection occurred during this period (Parker Williams and Hunt, 2002, 2004). Two sets of plots were established in the study area using a 1991 Landsat 5 Thematic Mapper image to define and locate the different vegetation types. The first set were circular plots (46 m diameter) used for determining cover of leafy spurge (Parker Williams and Hunt, 2002). The second set were square plots (50 m by 50 m) used for classification accuracy (Parker Williams and Hunt, 2004). Because all plots in the first set had some leafy spurge, these plots were combined with the second set to increase the number of points for classification accuracy assessment.

Ground Data Collection

Canopy spectral reflectance factors and were acquired in June 1999 using an ASD FieldSpec UV/VNIR Spectrometer (Analytical Spectral Devices, Inc., Boulder, Colorado, USA), and a Spectralon white panel. The instrument measures the spectral radiant flux density from 350 to 1050 nm wavelength; however, only the data from about 400 nm to about 900 nm were used. Endmember spectra were obtained at a height of 0.5 m for flowering and non-flowering leafy spurge canopies, residues, bare soils, shadow, and various other plant species. Nineteen 1.0-m by 1.5-m plots were established with a large range of flower-bract cover (Fig. 3). Ten canopy reflectance spectra were acquired at a height of about 1.3 m evenly spaced over each plot and averaged. A digital photograph of the plot was acquired from a Kodak DC120 1.2 megapixel digital camera (Eastman Kodak Company, Rochester, New York, USA), mounted on a pole and crossbar at 1.7-m height, so that the coverage on the ground was equal to the plot size.

Percent cover of flower-bracts was determined using a minimum-distance supervised classification in the Environment for Visualizing Images (ENVI, ITT Visual Information Solutions, Boulder, Colorado). Other components in these photographs were the cover of sunlit and shaded leaves, residue, grasses, forbs, bare soil, and shadow. The original purpose of this experiment was to determine the lower detection limit of leafy spurge using spectral mixture models; thus, most plots had low amounts of flowering leafy spurge (Fig. 3a).

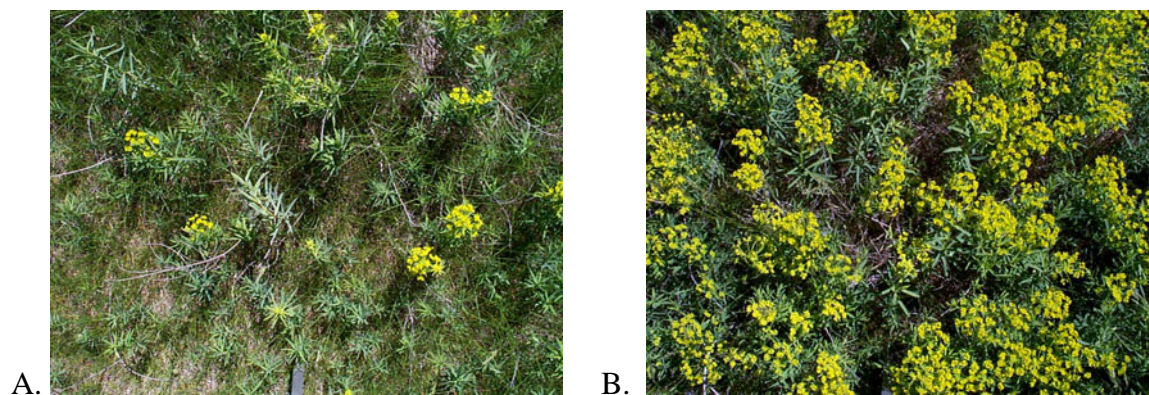


Figure 3. Digital photographs of field plots with A. 2% and B. 24% cover of flowering shoots. Dimensions of the photographs are 1 by 1.5 meters

The SAIL model

The Scattering by Arbitrarily Inclined Leaves (SAIL) model (Verhoef, 1984) uses reflectance and transmittance spectra of leaves to predict the directional reflectance of a uniform plant canopy. The code for the version of the SAIL model used in this study was written in Basic for Microsoft's Disk Operating System (MS-DOS) by Kim (1994), based upon the SAIL Fortran code written by Alexander (1983) and modified by Goward and Huemmrich (1992). Then, a graphical user interface for Microsoft Windows was written in Microsoft Visual Basic, along with an "install" program, which is available at: <http://www.ars.usda.gov/Services/software/download.htm?softwareid=12>.

Each layer of the canopy is comprised of numerous, small flat leaves specified by a leaf area index (LAI) and a leaf angle distribution (LAD). The number of plane-parallel canopy layers can vary from 1 to 9, and the background soil surface is assumed to be a Lambertian diffuse reflector. LAI of each layer is determined from the total canopy LAI divided by the number of canopy layers. LAD is determined by the proportion of leaves from 0 (vertical) to 90° (horizontal) in 10° increments, with the midpoints of each increment (5°, 15°, ..., 85°) used for the leaf angle calculations. The azimuth of the leaves in each layer is assumed to be random, which is sufficient if the leaves are not heliotropic (Verhoef, 1984). Each layer is comprised of one to nine canopy components, where each component has a specified percent cover, LAD, reflectance and transmittance. The layer LAD, reflectance and transmittance are the weighted averages determined by the proportion of each component.

The SAIL model does not handle discontinuous canopies, where taller plants cast shadows and bare ground is exposed (Verhoef, 1984). Therefore, there is a limit to which simulated and measured canopy reflectance spectra will agree, particularly for canopies with significant amounts of shadow; shadow is a critical endmember for spectral mixture models (Roberts et al., 1993, 1998). Current usage of the SAIL model is to predict the canopy reflectances for nadir-viewing satellites and airborne sensors to assess how leaf optical properties and canopy architecture scales up to affect vegetation indices (Goward and Huemmrich, 1992; Fourty and Baret, 1997; Huemmrich and Goward, 1997; Daughtry et al., 2000). The SAIL model is also combined with the PROSPECT leaf biochemistry model for use in reflectance and imaging spectroscopy (Jacquemoud et al., 2009).

Flower-bracts and leaves of leafy spurge were assumed to have a typical planophile (horizontal) LAD, other green vegetation was assumed to have a spherical LAD (Goel, 1988). The SAIL model simulations included various combinations of LAI, leaf cover and flower-bract cover. Leaves were placed in the bottom canopy layer, whereas flower-bracts were placed in the top canopy layer. The fraction of direct solar radiation was 90%, declination was 23°, latitude was 44.5°, time of day was 10:30 AM Mountain Standard Time, and view direction was nadir. SAIL model output was used to obtain target or reference spectra for calculation of spectral angles (Eq. 1). The reference spectra were either the measured canopy reflectance spectra or the simulated canopy reflectance spectra with LAI = 2.0, 50% flower-bract cover and 50% leaf cover.

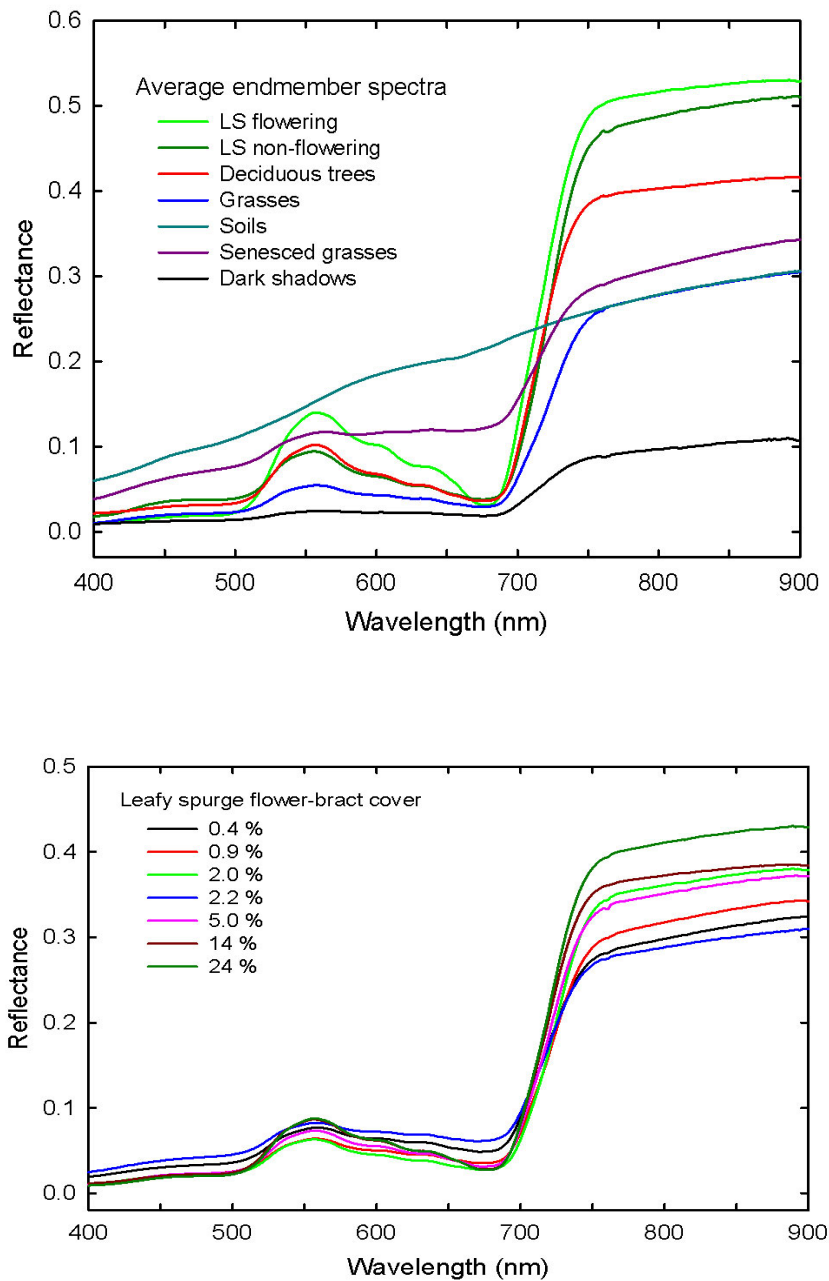


Figure 4. Spectral reflectances acquired using the ASD FieldSpec UV/VNIR spectrometer for: A. various spectral endmembers and B. field plots with a range in cover of flowering leafy spurge. Plot spectra are the average of 10 measurements and the endmember spectra are the average of 5 to 10 measurements.

Image Analyses

AVIRIS was flown at high altitude (20-m pixels) over the study site on July 6, 1999 (Parker Williams and Hunt, 2002). The AVIRIS data were atmospherically corrected using the ATREM 3.1 program (Gao et al., 1993, 1999). The atmospherically-corrected reflectances in the visible and near-infrared were smoothed using an empirical line correction obtained with the ASD FieldSpec UV/NIR spectrometer measurements over a large talus field at the base of Devils Tower (Parker Williams and Hunt, 2002). The high-altitude AVIRIS imagery did not have geometric lookup tables in 1999, therefore the three AVIRIS flight lines (11 scenes total, 48 contiguous bands in the visible and near-infrared from 449 nm to 912 nm) were registered to a SPOT image. The RMSE between the AVIRIS and SPOT images was 26 m; however, the overlap between the flightlines showed some areas were misregistered by as much as 8 pixels (160 m).

The AVIRIS images were classified for flowering leaf spurge using the Spectral Angle Mapper in ENVI. The reference spectrum was obtained from a large field known to have very high cover of flowering leafy spurge in 1999. Pixels with spectral angles (Eq. 1) that were less than or equal to a threshold value were classified as leafy spurge present and pixels with spectral angles that were greater than the threshold value were classified as leafy spurge absent. The threshold value was determined by the classification with the highest overall accuracy.

Results and Discussion

Spectral angles from field plot spectra

The average endmember spectrum of flowering leafy spurge is spectrally distinct from green leaves with higher reflectances at green and near-infrared wavelengths (Fig. 4a). The average shadow endmember shows there is a considerable amount of multiple scattering between the vegetation and soils (Ray and Murray, 1995). The field plot spectra show a large amount of variability because each plot had different amounts of grass, residue, bare soil, shadow, and flowering leafy spurge. The plots with the greatest amount of flowering leafy spurge cover had slightly higher reflectances at both green and near infrared wavelengths (Fig. 4b).

The range of total cover of leafy spurge (sum of flower-bract and leaf cover) varied from 0 to 95% in the 19 field plots, but the range of flower-bract cover was smaller because not all of the shoots were flowering (Fig. 3b, 4b). Flower-bract cover was significantly correlated with total cover of leafy spurge ($r = 0.798$, $P < 0.0001$).

Using the flowering leafy spurge endmember as a reference, the minimum Θ from the field data was about 2° for flower-bract cover $\geq 10\%$ (Fig. 5a), which corresponds to about $\geq 30\%$ total cover of leafy spurge. The largest values of Θ (Fig. 5a) corresponded with plots that were mostly residue and grass. When the field plot spectra were compared to other spectral endmembers, plots with high amounts of flower-bract cover were spectrally similar to green vegetation, but were not spectrally similar to other endmembers (Fig. 5b). With a linear spectral mixture model, 17 of 19 plots would have only the flower-bract and green-vegetation endmembers, but the calculated cover fractions did not agree with the measured cover fractions.

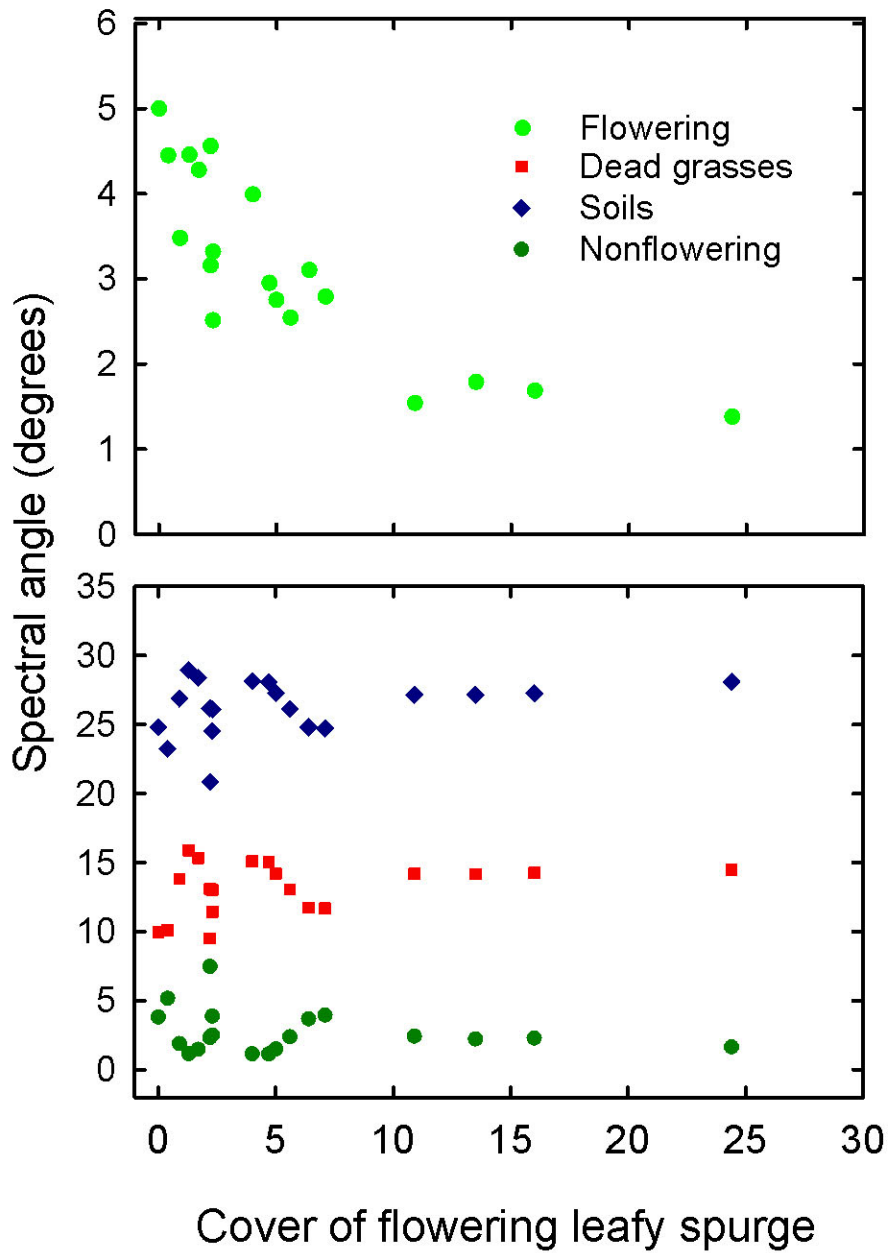


Figure 5. Spectral angles of target field plots using different endmember spectra: A. flowering leafy spurge; B. dead grasses, soils, and non-flowering leafy spurge.

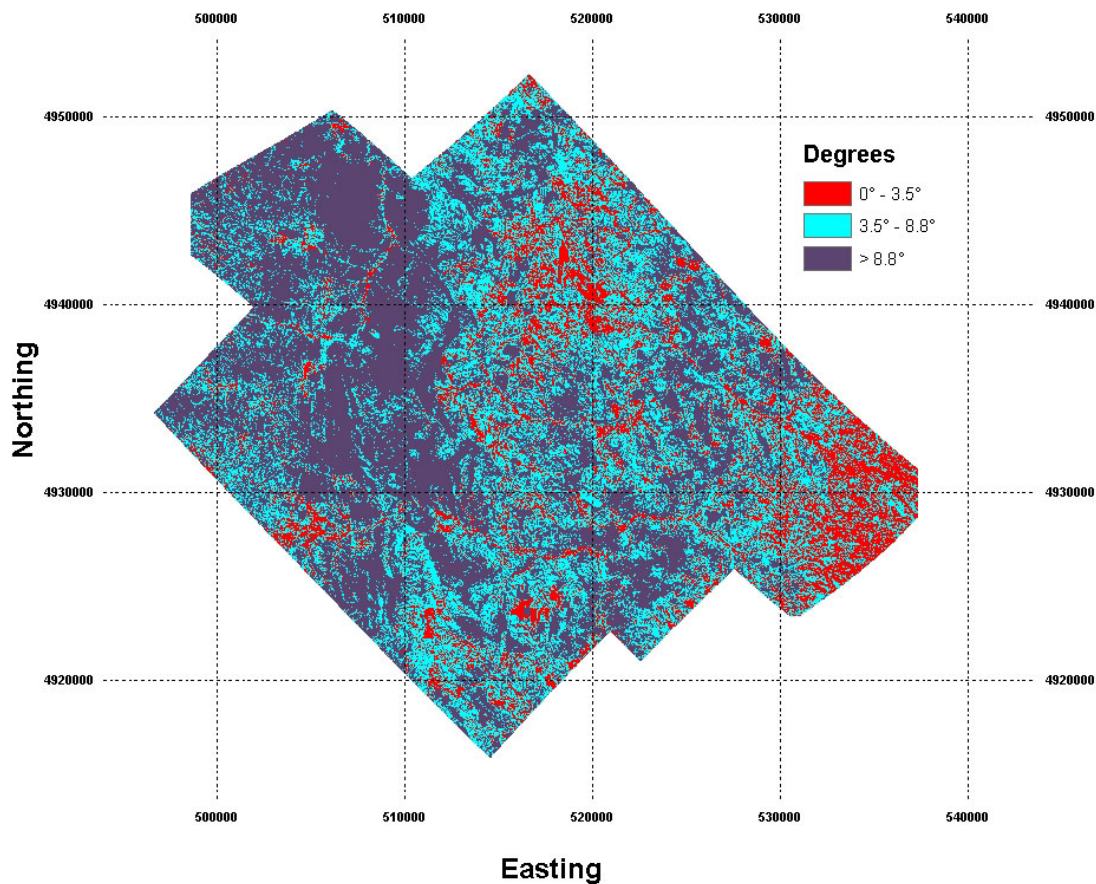


Figure 6. Classification of flowering leafy spurge for 11 AVIRIS scenes (48 bands from 449 to 912 nm) using the Spectral Angle Mapper. Areas in red are predicted to be leafy spurge, using a threshold of 3.5° (0.06 radians). The reference spectrum was obtained from a field in the image with a high amount of flowering leafy spurge cover.

Classifications of AVIRIS imagery using Spectral Angle Mapper

The reference spectrum for the Spectral Angle Mapper was selected from the AVIRIS image using 48 bands of AVIRIS imagery (Fig. 6). A threshold value of Θ was determined to be 3.5° from maximizing classification accuracy. The final overall accuracy was 74% for the classification of flowering leafy spurge. The k-hat statistic was 0.49, which was significant at $P < 0.0001$. The producer accuracy for leafy spurge was 63% and the user accuracy was 93%. Flowering leafy spurge covered 16% of the study area in a Spectral Angle Mapper classification. Most of the flowering leafy spurge was located in riparian corridors and draws. Pixels with green vegetation (based on high NDVI) had Θ from 3.5° to 8.8° and covered 34% of the study area. Areas with low amounts of vegetation (as indicated by field surveys and low values of NDVI) generally had Θ greater than 8.8° , which covered 50% of the study area (Fig. 6).

The pixel Θ for the 46-m diameter cover plots (Parker Williams & Hunt, 2002) and the Θ for 50-m square plots with zero leafy spurge cover were extracted from the classification in Fig. 6. The pixel Θ for the zero-leafy-spurge-cover plots ranged from 2° to 23° , whereas the Θ with some flowering leafy spurge ranged from 0.7° to 13° . Without the zero-leafy-spurge-cover plots, there was a weak correlation between the spectral angle and the amount of flower-bract cover ($r = 0.24$, $P < 0.05$). Parker Williams & Hunt (2002) found a much stronger relationship between the score from mixture-tuned matched filtering and the amount of leafy-spurge cover.

Furthermore, the overall classification accuracy with the Spectral Angle Mapper was lower than found by Parker Williams and Hunt (2004). Using mixture-tuned matched filtering to classify the eleven combined scenes of AVIRIS data (Fig. 6), the overall classification accuracy was considerably lower (49%) and not significantly better than chance. Parker Williams and Hunt (2004) analyzed two AVIRIS scenes independently. The increase in the number of scenes is expected to increase the number of spectral endmembers, which would lower the probability of detecting a single endmember (Joe Boardman, personal communication). Other studies found lower accuracies classifying leafy spurge with mixture-tuned matched filtering (Dudek et al., 2004; Glenn et al., 2005; Mitchell and Glenn, 2009a, 2009b), so more research is required for classifying imaging spectrometer data.

Assessing endmember variability using canopy radiative transfer models

Leaf area index (LAI) strongly influences simulated canopy spectral reflectances (Fig. 7). Absorption features due to chlorophyll and liquid water show little change with LAI from 3.0 to $4.0 \text{ m}^2 \text{ m}^{-2}$, whereas reflectances in the near-infrared are not saturated (Fig. 7). The same trends of simulated canopy reflectances with increasing LAI occur for different amounts of leafy spurge flower-bract cover. These simulations show there is a large range of possible variation which would strongly affect the calculated spectral angles (Θ , radians or degrees) for the detection of leafy spurge.

The reference spectrum was selected to have an LAI = $2.0 \text{ m}^2 \text{ m}^{-2}$ and 50% flower-bract cover, which was a reasonable representation of flowering leafy spurge occurring in a field at Devils Tower National Monument. The target spectra were the output from the other SAIL-model simulations. For all LAI, the greater the amount of flower-bract cover for each target spectrum, there was a smaller value of Θ (Fig. 8). At low LAI = $0.5 \text{ m}^2 \text{ m}^{-2}$, Θ between the reference spectrum and target spectra were greater than 4° for various amounts flower-bract cover. At higher LAI, Θ was less than 3.5° when flower-bract cover was 10% or greater (Fig. 8). If the LAI for the reference spectrum was set to be more extreme, then there would be more variation in Θ (data not shown).

Price (1994) and Cochrane (2000) concluded that most plant species are spectrally similar based on Θ calculations and other measures of spectral divergence. One of the problems of their analyses is that there is no independent standard to judge when Θ is sufficiently large to show spectral differences. The threshold values of $\Theta = 3.5^\circ$ is consistent with the AVIRIS classification accuracies from the Spectral Angle Mapper (Fig. 6). Thus, $\Theta > 3.5^\circ$ may be a reasonable criterion for spectral divergence. Once a threshold Θ and a reference spectrum

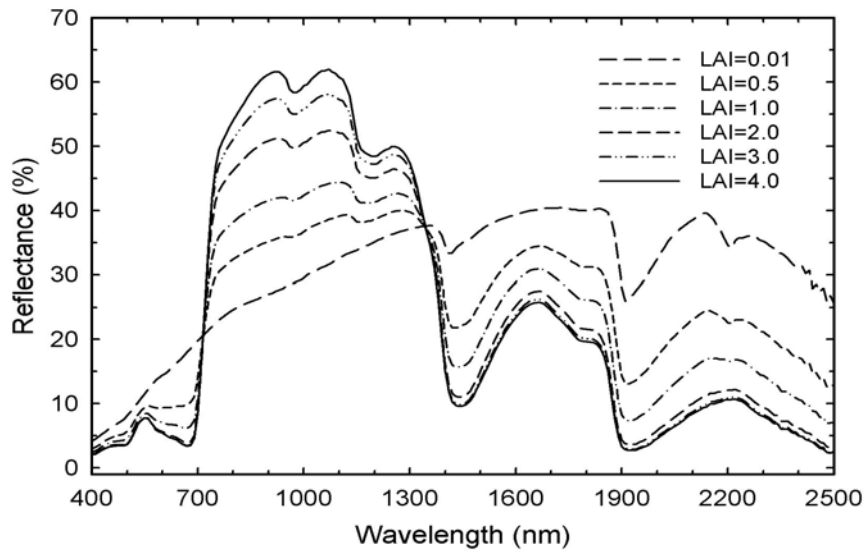


Figure 7. Simulated canopy reflectance spectra for various leaf area index (LAI) from the SAIL model. The cover of leafy spurge was 50% flower-bracts and 50% leaves and both leaves and flower-bracts had a planophile leaf angle distribution

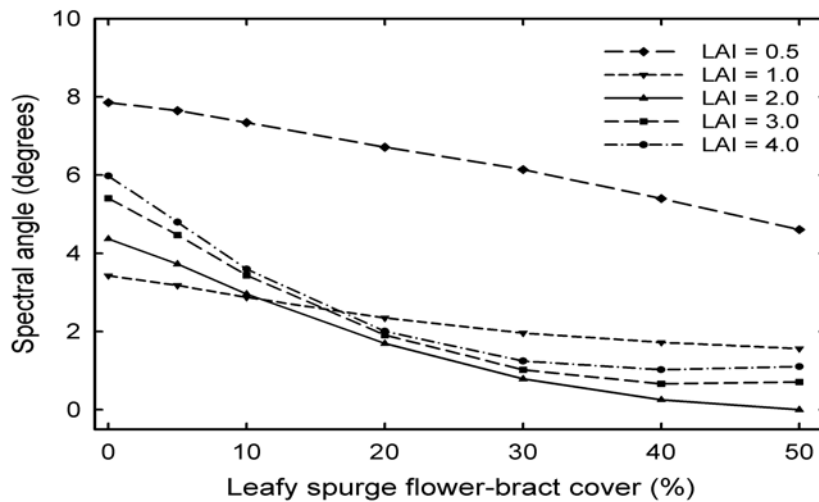


Figure 8. Spectral angles for various combinations of LAI and flower-bract cover from SAIL-model simulations. The reference spectrum had 50% flower-bract cover and an LAI = 2.0.

are determined a priori, then simulations using canopy reflectance models can be assessed to determine the conditions and sensors that are required for successful detection of an invasive species (Hunt et al., 2007).

The SAIL model is designed for a one-dimensional homogeneous canopy; hence, it cannot simulate shadows cast by taller plants, which are an important feature of three-dimensional canopy models. Shadows are an important endmember in spectral mixture models (Roberts et al., 1993, 1998; Fitzgerald et al., 2005), so SAIL model simulations cannot be used to generate the actual endmembers for application to imaging spectrometer data. In Fig. 6, the actual endmember for flowering leafy spurge was selected from the image. On the other hand, there is often considerable variation in spectral endmembers for the same species which may exceed the selected threshold Θ (Sohn and McCoy, 1997; Cochrane, 2000; Underwood et al., 2003; Mundt et al., 2005; Sohn and Qi, 2005). The variation in endmembers could be the result of different LAI, LAD, or differences in soil background, all of which are accounted for using the SAIL model.

Statistical significance of overall classification accuracy using the k -hat statistic does not mean that the Spectral Angle Mapper is useful for mapping out all areas infested by leafy spurge, because the selected threshold Θ was only appropriate for heavy infestations. Furthermore, the relationship between Θ and classification accuracy (Fig. 6) does not indicate if other classification methods would produce better results. The Spectral Angle Mapper normalizes brightness differences between the reference and target spectra (Kruse et al., 1993), so only spectral differences are distinguished; other methods use brightness differences for classification. Clark et al. (2005) found that the spectral angle mapper provided the poorest accuracy for identifying tropical-tree species compared to a linear discriminant analysis and maximum likelihood, but the differences among the species were not spectral, and thus the results of Clark et al. (2005) are expected.

The minimum cover for detection of leafy spurge flower bracts is about 10%, which is equal to about 35% total cover of leafy spurge. Currently, various species of flea beetles (*Aphthona* spp.) are used as biological control agents for leafy spurge (Kirby et al., 2000; Lesica and Hanna, 2009). One of the requirements for successful use of flea beetles is a large initial cover of leafy spurge in order to provide sufficient habitat for explosive population growth. So if leafy spurge is detected, then that area could be managed using biological control.

Conclusions

Measurements of spectral angles were used on the SAIL model output to determine a threshold spectral angle (Θ) that could be used to separate flowering leafy spurge from co-occurring native vegetation. Specifically, SAIL model simulations were used to account for variations in flower-bract cover fraction and LAI independently, something that is difficult to do when establishing field plots. Natural variation in LAI must be accounted for in the detection of leafy spurge (Glenn et al., 2005; Hunt and Parker Williams, 2006; Hunt et al., 2007). Leafy

spurge has been shown many times to be detectable using remote sensing, so it was expected that the results of this study would show a strong relationship between Θ and classification accuracies.

The results are extended to propose a methodology, which could use spectral libraries, to evaluate the potential for other invasive weeds to be detected by remote sensing. Then, various sensors could be used to test predictions and to assess the classification accuracies with respect to user needs. Knowledge of the conditions where detection is likely to be good or fail will also assist in establishing field plots for accuracy assessment, because cover, LAI and soil background are shown to be important variables affected detection accuracy. Not all invasive species are as distinctive as leafy spurge, and many species probably will not be detectable (Price, 1994; Cochrane, 2000); evaluating the detection potential of a particular invasive species before image acquisition and field work should save time and money which could be used for other monitoring activities.

Acknowledgments

Ralph Roberts programmed the graphical user interface for the SAIL model. Field data were obtained by Amy E. Parker Williams from the University of Wyoming. Mention of trade names is for information only and does not imply endorsement by USDA.

References

- Alexander, L. 1983. SAIL Canopy Model Fortran Software. NASA Technical Report JSC-18899, NASA Johnson Space Center, Houston, Texas, USA.
- Anderson, G. L., Delfosse, E. S., Spencer, N. R., Prosser, C. W., and Richard, R. D. 2003. Lessons in developing successful invasive weed control programs. *Journal of Range Management* 56: 2-12.
- Anderson, G. L., Everitt, J. H., Escobar, D. E., Spencer, N. R., & Andrascik, R. J. 1996. Mapping leafy spurge (*Euphorbia esula*) infestations using aerial photography and geographic information systems. *Geocarto International* 11: 81-89.
- Andrew, M. E. and Ustin, S. L. 2008. The role of environmental context in mapping invasive plants with hyperspectral image data. *Remote Sensing of Environment* 112:4301-4317.
- Casady, G. M., Hanley, R. S., and Seelan, S. K. 2005. Detection of leafy spurge (*Euphorbia esula*) using multirate high-resolution satellite imagery. *Weed Technology* 19: 462-467.
- Clark, M. L., Roberts, D. A., and Clark, D. B. 2005. Hyperspectral discrimination of tropical rain forest tree species at leaf to crown scales. *Remote Sensing of Environment* 96: 375-398.
- Cochrane, M. A. 2000. Using vegetation reflectance variability for species level classification of hyperspectral imagery. *International Journal of Remote Sensing* 21: 2075-2087.
- Daughtry, C. S. T., Walthall, C. L., Kim, M. S., Brown de Colstoun, E., and McMurtrey, J. E., III. 2000. Estimating corn leaf chlorophyll concentration from leaf and canopy reflectance. *Remote Sensing of Environment* 74: 229-239.

- Dudek, K. B., Root, R. R., Kokaly, R. F. and Anderson, G. L. 2004. Increased spatial and temporal consistency of leafy spurge maps from multirate AVIRIS imagery: A modified, hybrid linear spectral mixture analysis/mixture-tuned matched filtering approach. In R. O. Green (Ed.), Proceedings of the 13th JPL Airborne Earth Sciences Workshop Pasadena, California, NASA Jet Propulsion Laboratory.
- Everitt, J. H., Anderson, G. L., Escobar, D. E., Davis, M. R., Spencer, N. R., and Andrascik, R. J. 1995a. Use of remote sensing for detecting and mapping leafy spurge (*Euphorbia esula*). Weed Technology 9: 599-609.
- Everitt, J. H., Escobar, D. E., and Davis, M. R. 1995b. Using remote sensing for detecting and mapping noxious plants. Weed Abstracts 44: 639-649.
- Everitt, J. H., Yang, C., Escobar, D. E., and Davis, M. R. 2002. Using remote sensing to detect and map invasive plant species. Annals of Arid Zone 41: 321-342.
- Fitzgerald, G. J., Pinter, P. J., Jr., Hunsaker, D. J., and Clarke, T. R. 2005. Multiple shadow fractions in spectral mixture analysis of a cotton canopy. Remote Sensing of Environment 97: 526-539.
- Fourty, T. and Baret, F. 1997. Vegetation water and dry matter contents estimated from top-of-the-atmosphere reflectance data: A simulation study. Remote Sensing of Environment 61: 34-45.
- Gao, B.-C., Heidebrecht, K. B., and Goetz, A. F. H. 1993. Derivation of scaled surface reflectances from AVIRIS data. Remote Sensing of Environment 44: 145-163.
- Gao, B.-C., Heidebrecht, K. B., & Goetz, A. F. H. 1999. Atmosphere REMoval Program (ATREM) User's Guide, Version 3.1. Boulder, Colorado: Center for the Study of Earth from Space (CSES), Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado.
- Gates, D. M., Keegan, H. J., Schleter, J. C., and Weidner, V. R. 1965. Spectral properties of plants. Applied Optics 4: 11-20.
- Glenn, N. F., Mundt, J. T., Weber, K. T., Prather, T. S., Lass, L. W., and Pettingill, J. 2005. Repeat hyperspectral data processing for the detection of small infestations of leafy spurge. Remote Sensing of Environment 95: 399-412.
- Goel, N. S. 1988. Models of vegetation canopy reflectance and their use in estimation of biophysical parameters from reflectance data. Remote Sensing Reviews 4: 1-212.
- Goward, S. N. and Huemmrich, K. F. 1992. Vegetation canopy PAR absorptance and the normalized difference vegetation index: an assessment using the SAIL model. Remote Sensing of Environment 39: 119-140.
- Huemmrich, K. F. and Goward, S. N. 1997. Vegetation canopy PAR absorptance and NDVI: An assessment for ten tree species with the SAIL model. Remote Sensing of Environment 61: 254-269.
- Hunt, E. R., Jr., Daughtry, C. S. T., Kim, M. S., and Parker Williams, A. E. 2007. Using canopy reflectance models and spectral angles to assess potential of remote sensing to detect invasive weeds. Journal of Applied Remote Sensing 1:013506 (online).
- Hunt, E. R., Jr., McMurtrey, J. E., III, Parker Williams, A. E., and Corp, L. A. 2004. Spectral characteristics of leafy spurge (*Euphorbia esula*) leaves and flower bracts. Weed Science 52: 492-497.

- Hunt, E. R., Jr. and Parker Williams, A. E. 2006. Detection of flowering leafy spurge with multispectral satellite imagery. *Rangeland Ecology & Management* 59:494-499.
- Jacquemoud, S., Verhoef, W., Beret, F., Bacour, C., Zarco-Tejada, P. J., Asner, G. P., François, C., and Ustin, S. L. 2009. PROSPECT+SAIL models: A review of use for vegetation characterization. *Remote Sensing of Environment* 113: S56-S66.
- Kim, M. S. 1994. The Use of Narrow Spectral Bands for Improving Remote Sensing Estimation of Fractionally Absorbed Photosynthetically Active Radiation (f_{APAR}), MS Thesis. College Park, Maryland: Department of Geography, University of Maryland.
- Kirby, D. R., Carlson, R. B., Krabbenhoft, K. D., Mundal, D., and Kirby, M. M. 2000. Biological control of leafy spurge with introduced flea beetles (*Aphthona* spp.). *Journal of Range Management* 53: 305-308.
- Knipling, E. B. 1970. Physical and physiological basis for the reflectance of visible and near-infrared radiation from vegetation. *Remote Sensing of Environment* 1: 155-159.
- Kruse, F. A., Lefkoff, A. B., Boardman, J. W., Heidebrecht, K. B., Shapiro, A. T., Barloon, P. J., and Goetz, A. F. H. 1993. The spectral image processing system (SIPS) - interactive visualization and analysis of imaging spectrometer data. *Remote Sensing of Environment* 44: 145-163.
- Lass, L. W., Prather, T. S., Glenn, N. F., Weber, K. T., Mundt, J. T., and Pettingill, J. 2005. A review of remote sensing of invasive weeds and example of the early detection of spotted knapweed (*Centaurea maculosa*) and babysbreath (*Gypsophila paniculata*) with a hyperspectral sensor. *Weed Science* 53: 242-251.
- Lass, L. W., Thill, D. C., Shafii, B., and Prather, T. S. 2002. Detecting spotted knapweed (*Centaurea maculosa*) with hyperspectral remote sensing technology. *Weed Technology* 16: 426-432.
- Lawrence, R. L., Wood, S. D., and Sheley, R. L. 2006. Mapping invasive plants using hyperspectral imagery and Breiman Cutler classifications (RandomForest). *Remote Sensing of Environment* 100: 356-362.
- Lesica, P. and Hanna, D. 2009. Effect of biological control on leafy spurge (*Euphorbia esula*) and diversity of associated grasslands over 14 years. *Invasive Plant Science and Management* 2: 151-157.
- Major, D. J., Schaalje, G. B., Wiegand, C., and Blad, B. L. 1992. Accuracy and sensitivity analyses of SAIL model-predicted reflectance of maize. *Remote Sensing of Environment* 41: 61-70.
- Mitchell, J. J. and Glenn, N. F. 2009a. Subpixel abundance estimates in mixture-tuned matched filtering classifications of leafy spurge (*Euphorbia esula* L.). *International Journal of Remote Sensing* 30: 6099-6119.
- Mitchell, J. J. and Glenn, N. F. 2009b. Leafy spurge (*Euphorbia esula*) classification performance using hyperspectral and multispectral sensors. *Rangeland Ecology & Management* 62: 16-27.
- Mladinich, C. S., Ruiz Bustos, M., Stitt, S., Root, R., Brown, K., Anderson, G. L., and Hager, S. 2006. The use of Landsat 7 Enhanced Thematic Mapper Plus for mapping leafy spurge. *Rangeland Ecology & Management* 59:500-506.

- Mundt, J. T., Glenn, N. F., Weber, K. T., Prather, T. S., Lass, L. W., & Pettingill, J. 2005. Discrimination of hoary cress and determination of its detection limits via hyperspectral processing and accuracy assessment techniques. *Remote Sensing of Environment* 96: 509-517.
- O'Neill, M., Ustin, S. L., Hagar, S., and Root, R. 2000. Mapping the distribution of leafy spurge at Theodore Roosevelt National Park using AVIRIS. In R. O. Green (Ed.), *Proceedings of the 9th JPL Airborne Earth Sciences Workshop*, JPL Publication 00-18 (pp. 339-347). Pasadena, California: NASA Jet Propulsion Laboratory.
- Parker Williams, A. E. and Hunt, E. R., Jr. 2002. Estimation of leafy spurge cover from hyperspectral imagery using mixture tuned matched filtering. *Remote Sensing of Environment* 82: 446-456.
- Parker Williams, A. E. and Hunt, E. R., Jr. 2004. Accuracy assessment for detection of leafy spurge with hyperspectral imagery. *Journal of Range Management* 57: 106-112.
- Price, J. C. 1994. How unique are spectral signatures? *Remote Sensing of Environment* 49: 181-186.
- Ray, T. W. and Murray, B. C. 1995. Nonlinear spectral mixing in desert vegetation. *Remote Sensing of Environment* 55: 59-64.
- Roberts, D. A., Gardner, M., Church, R., Ustin, S., Scheer, G., and Green, R. O. 1998. Mapping chaparral in the Santa Monica Mountains using multiple endmember spectral mixture models. *Remote Sensing of Environment* 65: 267-279.
- Roberts, D. A., Smith, M. O., and Adams, J. B. 1993. Green vegetation, nonphotosynthetic vegetation, and soils in AVIRIS data. *Remote Sensing of Environment* 44: 255-269.
- Sohn, Y. and McCoy, R. M. 1997. Mapping desert shrub rangeland using spectral unmixing and modeling spectral mixtures with TM data. *Photogrammetric Engineering & Remote Sensing* 63: 707-716.
- Sohn, Y. and Qi, J. 2005. Mapping detailed biotic communities in the upper San Pedro Valley of Southeastern Arizona using Landsat 7 ETM+ data and supervised spectral angle classifier. *Photogrammetric Engineering & Remote Sensing* 71: 709-718.
- Underwood, E., Ustin, S., and Dipietro, D. 2003. Mapping nonnative plants using hyperspectral imagery. *Remote Sensing of Environment* 86: 150-161.
- Ustin, S. L., Roberts, D. A., Gamon, J. A., Asner, G. P., and Green, R. O. 2004. Using imaging spectroscopy to study ecosystem processes and properties. *Bioscience* 54: 523-534.
- Verhoef, W. 1984. Light scattering by leaf layers with application to canopy reflectance modeling: the SAIL model. *Remote Sensing of Environment* 16: 125-141.