ELSEVIER

Spectral Discrimination of *Cannabis sativa* L. Leaves and Canopies

C. S. T. Daughtry and C. L. Walthall**

*The growing of marijuana (*Cannabis sativa L.*) on public lands poses problems to the environment and the public. Remote sensing offers a potential way of monitoring public lands for the production of marijuana. However, very little information on the spectral properties of marijuana is available in the scientific literature. Our objectives were to 1) characterize the spectral properties of the leaves of marijuana and various other plants that occur where marijuana is grown in the eastern United States, 2) simulate canopy reflectance, and 3) identify wavebands for discriminating marijuana from other plants. In a series of replicated field experiments, the basic factors affecting marijuana growth and reflectance, including planting date, plant density, and N-fertilization were varied. Leaf optical properties were measured periodically during the growing season with a spectroradiometer and integrating sphere. As N-fertilization rate decreased, the marijuana plants produced leaves with lower chlorophyll concentrations and higher reflectance values in the visible wavelength region, particularly at 550 nm. The reflectance spectra of the herbaceous dicot species examined were very similar to the spectrum of marijuana. The reflectance spectra of the monocots and the trees differed significantly from the spectrum of marijuana, particularly in the green and near-infrared wavelength regions. Canopy reflectance spectra of marijuana and several representative species were simulated for a wide range of LAI and background reflectances. Major differences in canopy reflectance of marijuana and other plants were observed near 550 nm, 720 nm, and 800 nm. Dense canopies of marijuana were more spectrally discriminable from other vegetation than sparse canopies. Thus, based on measured leaf spectra and simulated canopy reflectance spectra, we would choose several relatively narrow (i.e., 30 nm or less) spectral bands in the green (550 nm), red (670 nm), "red edge" (720 nm), and the near-infrared (800 nm) to discriminate marijuana leaves and canopies from other species. Much of the leaf spectral information is also available in the canopy reflectance data. Published by Elsevier Science Inc., 1998*

INTRODUCTION

The growing of cannabis or marijuana (*Cannabis sativa* L.) on public lands poses problems to the environment and the public. Not only are unauthorized disturbances to the environment created, more seriously, growers often set booby traps or post armed guards to protect their plots. This is especially important with respect to the use of our national forests by the public. Remote sensing offers a potential way of monitoring public lands for the production of cannabis. However, very little information on the spectral properties of marijuana is available in the scientific literature.

The spectral properties of vegetation and soils must be understood to identify plant species and to estimate plant productivity from remotely sensed data. When dealing with remote sensing of specific plants, as in agriculture and forestry, the problem is interpreting the reflected signal produced by the soil–plant–atmosphere system. The vegetation of interest, the underlying strata (such as soil, plant litter, other types of vegetation, or water, etc.), and the intervening atmosphere between the target and the sensor contribute to the sensor response. However, because plant leaves contribute most of the signal from vegetation, the spectral reflectance and transmittance of leaves are primary factors in understanding the reflectance of the full plant canopy.

For more than 3 decades, scientists have examined the biological and physical factors that affect leaf reflec-

* USDA/ARS, Remote Sensing and Modeling Laboratory, Beltsville, Maryland

Address correspondence to C. S. T. Daughtry, Remote Sensing and Modeling Lab., USDA/AR, Bldg. 007, BARC-West, 10300 Baltimore Ave., Beltsville, MD 20705-2350.

Received 17 October 1996; revised 9 December 1997.

REMOTE SENS. ENVIRON. 64:192–201 (1998)
Published by Elsevier Science Inc., 1998
655 Avenue of the Americas, New York, NY 10010

0034-4257/98/$00.00
PII S0034-4257(98)00002-9

Table 1. Common and Scientific Names of Plants Included in This Study and the Number Dates Sampled in Each Year[a]

Common Name	*Scientific Name*	*1993*	*1994*	*1995*	*1996*
1. Basil	*Ocimum basilicum*	0	0	4	0
2. Citronella	*Cymbopogon citronella*	0	0	4	0
3. Cleomas	*Cleome hasselerana*	0	0	4	0
4. Corn	*Zea mays* L.	0	2	4	1
5. Marijuana	*Cannabis sativa* L.	1	2	4	1[a]
6. Okra	*Hibiscus esculentus* L.	0	0	4	0
7. Soybean	*Glycine max* Merr.	0	2	4	0
8. Tomato	*Lycopersicon esculentum* Mill.	0	0	4	0
9. Velvetleaf	*Abutilon theophrasti*	0	0	4	0
10. Wheat	*Triticum aestivum* L.	0	0	0	4
11. Birch, gray	*Betula populifolia*	1	2	4	0
12. Hickory, shag bark	*Carya ovata*	1	2	4	0
13. Maple, red	*Acer rubrum*	1	1	4	0
14. Oak, red	*Quercus ruba*	1	1	4	0
15. Oak, white	*Quercus alba*	1	2	4	0
16. Poplar, yellow tulip	*Liriodendron tulipifera*	1	2	0	0
17. Sassafras	*Sassafras albidum*	1	2	4	0
18. Sweet gum	*Liquidamber styraciflua*	1	1	4	0
19. Willow, black	*Salix nigra*	0	1	0	0

[a] Includes plants from seeds acquired in Afghanistan, Colombia, Jamaica, Mexico, and the United States.

tance and transmittance, including plant species (e.g., Gausman and Allen, 1973; Woolley, 1971), leaf age (Gausman et al., 1971), leaf mesophyll arrangement (Gausman et al., 1969; 1973), chlorophyll content (Thomas and Oerther, 1972; Blackmer et al., 1994), and leaf water content (Woolley, 1971). Leaf reflectance has also been extensively reviewed (Gates et al., 1965; Knipling, 1970; Bauer, 1975; Grant, 1987). All chlorophyll-bearing healthy leaves have a similar characteristic spectral signature that consists of high absorption (low reflectance) in the visible and low absorption (high reflectance) in the near-infrared region. Knowledge of the differences in leaf reflectances is considered a useful starting point when looking for features to discriminate between species using spectral remote sensing. The amount of variability and the significance of the variability within and among species is still not understood.

Our objectives were to 1) characterize the spectral properties of the leaves of *Cannabis sativa* and various other plants that occur where marijuana is grown in the eastern United States, 2) simulate canopy reflectance, and 3) identify wavebands for discriminating marijuana from other plants.

MATERIALS AND METHODS

Experiment Description

Several annual and perennial plants (Table 1), growing on a Galestown–Evesboro sandy loam soil near Beltsville, Maryland, were sampled periodically in 1994, 1995, and 1996. Most of the annual plants were started from seeds in the greenhouse and transplanted to the field. Because *Cannabis sativa* L. is monoecious with pistillate and staminate flowers usually borne on separate plants (Clarke, 1981), we vegetatively propagated pistillate (female) plants by rooting stem cuttings to produce uniform plants. In 1996, additional marijuana plants were grown from seeds. The actual pedigrees of the marijuana used are unknown beyond the state or country where the seed were acquired. Plants from the following locations were grown in 1996; Afghanistan (two seed lots), Colombia, Jamaica, Mexico (two seed lots), and the United States (five seed lots). The perennial plants were trees growing near the field and were rain-fed only. The annual plants were drip-irrigated and well-fertilized according to University of Maryland's best management practices for high corn yields. In 1995, we also conducted a replicated field experiment with marijuana in which we used four of N application rates (0 kg N/ha, 50 kg N/ha, 100 kg N/ha, and 200 kg N/ha) to produce plants with a range of N-deficiency symptoms.

Leaf Spectra

A fully expanded leaf near the top of three plants of each species was selected, excised, placed in a plastic bag in an ice chest, and transported to the laboratory for spectral measurements. Leaf reflectance and transmittance were measured with a Li-1800[1] integrating sphere (Li-Cor, Inc., Lincoln, Nebraska) coupled to a SE590 Spectroradiometer (Spectron Engineering, Inc., Denver, Colorado) over the 400–1000 nm wavelength range at approximately 3-nm intervals. Both adaxial and abaxial surfaces of each leaf were measured and reflectance and transmittance factors were calculated (Daughtry et al.,

[1] Company and product names are used for clarity and do not imply any endorsement by USDA to the exclusion of other comparable products.

Table 2. Input Data for the SAIL Model

Input Parameters	*Input Values*
Leaf reflectance and transmittance	Marijuana, corn, soybean, okra, birch, and white oak
Background reflectance	Barnes (coarse-loamy, mixed Udic Haploboroll), from Morris, Minnesota
	Othello (fine-silty, mixed, mesic Typic Ochraquult), from Salisbury, Maryland
	Corn residue, 8 months after harvest, from Beltsville, Maryland
Leaf area index	0, 0.01, 0.1, 0.5, 1, 2, 4, 6, 8
Leaf angle distribution	Spherical
View zenith angle	0° (nadir)
Sun zenith angle	45°
Fraction of direct incoming radiation	1.0

1989). After the spectral measurements, a 131 mm^2 disk was cut from each leaf for pigment analysis. Each leaf disk was extracted for 24-h in the dark at 25°C with dimethyl sulfoxide (DMSO) after which the absorptance was measured. Concentrations of chlorophyll *a* and chlorophyll *b* were computed using the equations of Lichtenthaler et al. (1987).

In August 1993, we acquired leaves of marijuana plants confiscated by state and federal law enforcement officers in the Boone National Forest in Kentucky. Leaf reflectance and transmittance spectra were acquired as described above. Leaf spectra of various trees growing in the area were also acquired and are listed in Table 1.

Difference spectra were calculated by subtracting the reflectance spectra of the adaxial surface of marijuana leaves from the adaxial reflectance spectra of the other species. The difference spectra departed from zero at wavelengths where the spectra of marijuana and the other species differed. Positive values indicate that the reflectance of the other species is greater than that of marijuana. The deviations from the marijuana reference spectrum were also squared and summed over species and dates. Root mean square deviations ($\mathrm{RMSD}_{(\lambda,j)}$) were calculated as follows:

$$\mathrm{RMSD}_{(\lambda,j)}=\left(\sum_{i=1}^{n}[\rho_{(\lambda,i)}-\rho_{(\lambda,\mathrm{can})}]^2/n_j\right)^{1/2}, \qquad (1)$$

where $\rho_{(\lambda,i)}$ is the reflectance in waveband (λ) of species (i); $\rho_{(\lambda,\mathrm{can})}$ is the reflectance in waveband (λ) of marijuana leaves from plants fertilized with 200 kg N/ha; n_j represents the class (i.e., corn, trees, herbs) which has n_j species dates measured. RMSD was plotted as a function of wavelength to indicate spectral regions where the differences in reflectance between marijuana and other species occurred consistently.

Simulated Canopy Reflectance

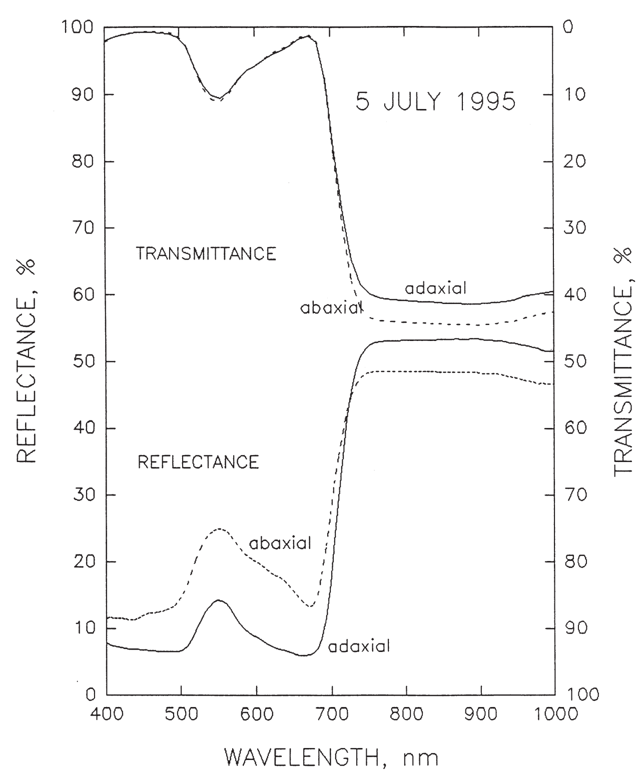
Canopy reflectance was simulated using the SAIL (Scattering by Arbitrarily Inclined Leaves) model (Verhoef, 1984). The SAIL model is a turbid-medium model that treats the canopy as a horizontally uniform plane-parallel layer with diffusely reflecting and transmitting elements (Goel, 1989). Canopy architecture is expressed through leaf area index (LAI) and leaf angle distribution (LAD). The soil or lowest layer is assumed to be a diffuse reflector. Input spectral data included leaf reflectance and transmittance of selected plants from 25 and 26 July 1995 and reflectance of two soils (i.e., Barnes and Othello) and one crop residue (Table 2). Daughtry et al. (1997) described the reflectance measurements of the soils and the crop residue. Other input conditions are listed in Table 2. Canopy reflectance factors were simulated for LAIs of 0, 0.01, 0.1, 0.5, 1, 2, 4, 6, and 8. Residual spectra were calculated by subtracting the canopy reflectance spectra of the marijuana from the canopy reflectance spectra of selected other species. Root mean square deviations (RMSD) were plotted as a function of wavelength for each LAI level.

RESULTS AND DISCUSSION

Marijuana Leaf Spectra

Mean reflectance and transmittance of the adaxial (upper) and abaxial (lower) surfaces of fully-expanded leaves of well-fertilized marijuana sampled on 5 July 1995 are shown in Figure 1. These plots exhibit the typical green

Figure 1. Spectral reflectance and transmittance of Colombian marijuana leaves on 5 July 1995. The leaves were from plants receiving 200 kg N/ha.



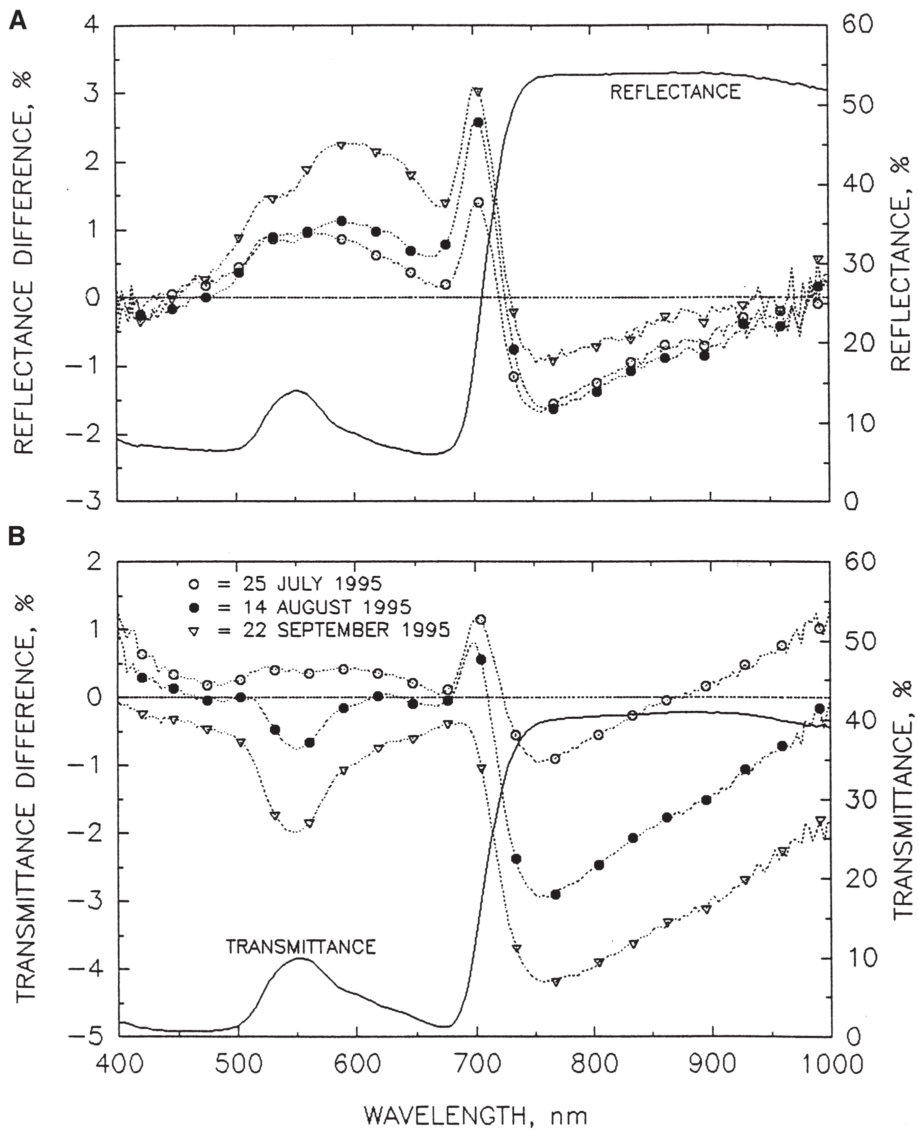


Figure 2. Differences in adaxial reflectance (A) and transmittance (B) of upper, fully expanded leaves of Colombian marijuana during the growing season. The mean spectrum for 5 July 1995 was subtracted from the mean spectrum for the other dates. The line at 0 indicates no change from the values on 5 July. The reflectance and transmittance spectra for 5 July are shown for reference.

leaf spectral form. The abaxial surface has higher reflectance in the visible region and lower reflectance in the near-infrared than the adaxial surface. Similar results were observed for both surfaces on each date but are not shown.

We subtracted the spectra on 5 July from spectra on each successive date to illustrate the changes in leaf reflectance and transmittance as the season progressed. The differences in reflectance and transmittance are summarized in Figure 2. Reflectance increased and transmittance decreased in the visible on each successive date, even though we sampled upper fully expanded leaves on each date. On the first two dates (5 and 25 July), the plants were vegetative, but on the last two dates (14 August and 22 September) the plants were producing seedless floral clusters (sinsemilla). The size and number leaflets per leaf decreased after flowering until only a small single leaflet appeared below each pair of calyxes as described by Clarke (1981). Because the single leaflet was generally too small to cover the sample port of the integrating sphere, we selected the uppermost leaf with leaflets wider than 15 mm on 22 September. Thus, the effect of date and age of leaf are confounded in the spectral data from August and September.

Nitrogen fertilization also affected leaf reflectance as shown in Figure 3. The reflectance spectra of the well-fertilized marijuana was subtracted from the reflectance spectra of the other treatments to emphasize the changes due to N-fertilization rate. On each date, the largest changes were observed near 550 nm and 700 nm wavelength region (Fig. 3). As N-fertilization rate decreased, the plants produced leaves with lower chlorophyll concentrations and higher mean reflectance in the visible wavelength region. The N-deficient plants contained less chlorophyll than the well-fertilized, control plants. These results demonstrate that chlorophyll concentration dominates spectral reflectance in the visible region of the spectrum and is an indicator of N-stress in plants. Similar results have been reported for a wide range of species, including corn (Al-Abbas et al., 1974; Blackmer et

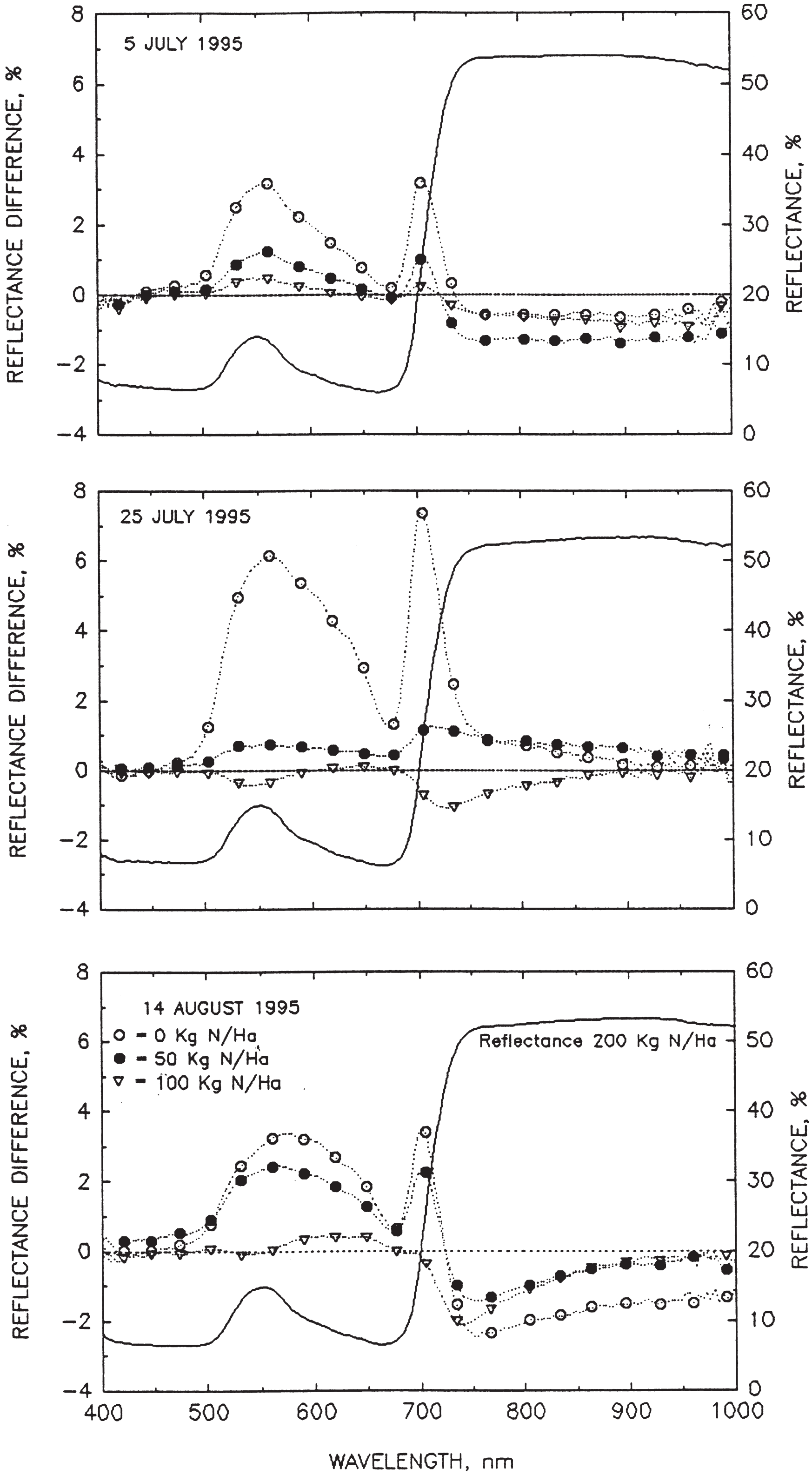


Figure 3. Effects of applied N on differences in reflectance spectra of Colombian marijuana leaves. The reflectance spectrum of leaves from plants receiving 200 kg N/ha was subtracted from the reflectance spectrum of leaves from plants receiving lower rates of applied N. The line at 0 indicates no change from the reflectance for 200 kg N/ha. The reflectance spectra for 200 kg N/ha rate are also shown for each date.

al., 1994), sweet pepper (Thomas and Oerther, 1972), and Douglas fir (Grant and Murtha, 1994).

The differences in the reflectance spectra of the various marijuana selections are relatively small (Fig. 4). The greatest differences appear to be in the green region near 550 nm and in the "red edge" region near 720 nm. The differences in the near-infrared reflectance of all the marijuana selections was less than 3%.

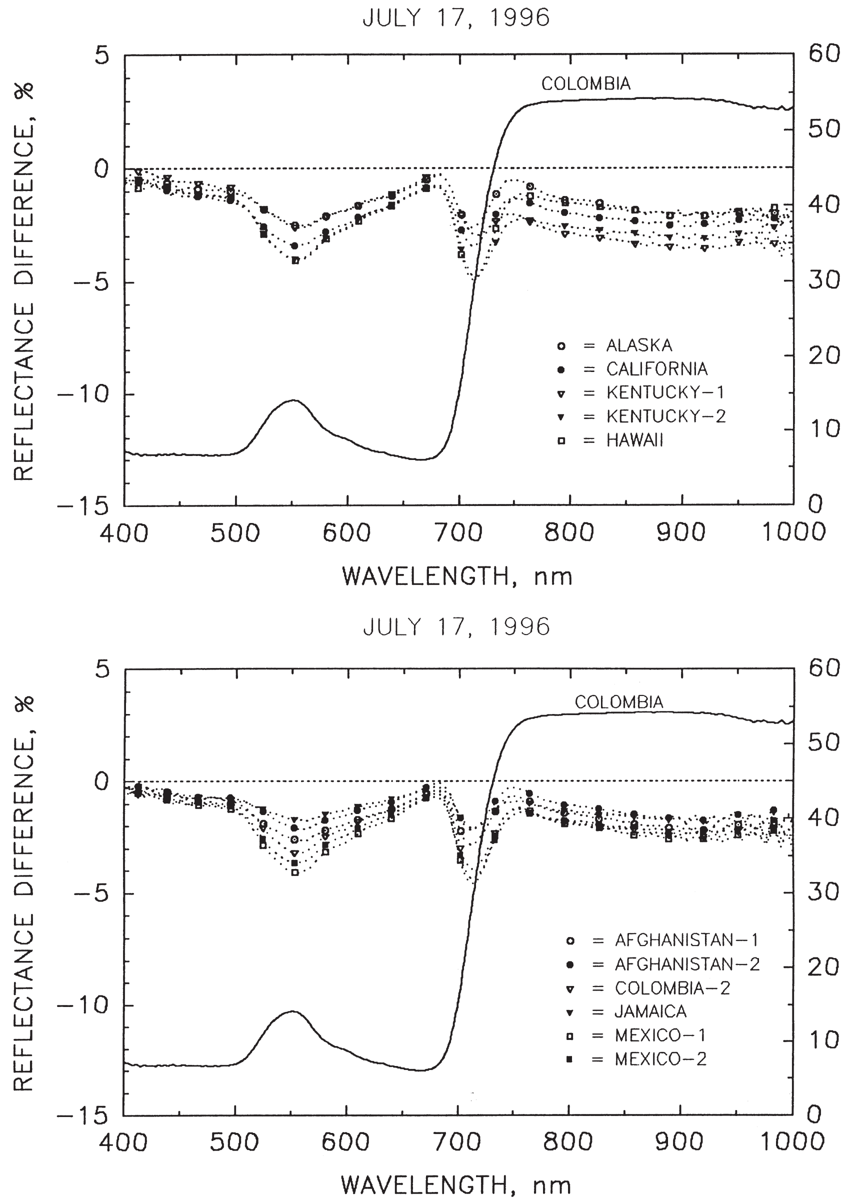


Figure 4. Differences in reflectance spectra of marijuana leaves from various seed sources. The mean reflectance spectrum of leaves from marijuana plants from Colombia was subtracted from the mean reflectance spectrum of leaves from other locations.

Leaf Spectra of Other Species

Leaf spectra of seven tree species and eight herbaceous species were also examined on four dates during the 1995 growing season. Differences in reflectance of adaxial leaf surface of these plants relative to marijuana leaf spectrum are shown in Figures 5 and 6. The reflectance of the tree leaves was less than the reflectance of the marijuana. Only the White Oak spectrum at 600–700 nm on 26 July was higher than the spectrum of marijuana. The greatest differences in reflectance were observed in the green region near 550 nm and in the transition from visible to the near-infrared region near 720 nm.

The reflectance spectra of most of the herbaceous plants were very similar to the spectrum of marijuana (Fig. 6). Corn, the only monocot represented, was a notable exception. In the near-infrared, the spectrum of corn was 5–10% lower than the spectrum of cannabis on each date and is consistent with previous observations of monocot and dicots (Gausman et al., 1973; Gausman and Allen, 1973). The porous, dorsiventral, mesophyll structure of most of the herbaceous dicot leaves contributed to their high near infrared reflectance. Corn and most monocots have a compact, leaf mesophyll structure, which contributes to their low near-infrared reflectance.

The root mean square deviations (RMSD) of the reflectance spectra are plotted as a function of wavelength in Figure 7 for 1995 (the other years were similar, but are not shown). The RMSD values represent means over species and dates. The RMSD curves graphically summarize the spectral data presented in the previous figures and show where the spectra of the other species deviate from the spectrum of marijuana. If the spectra

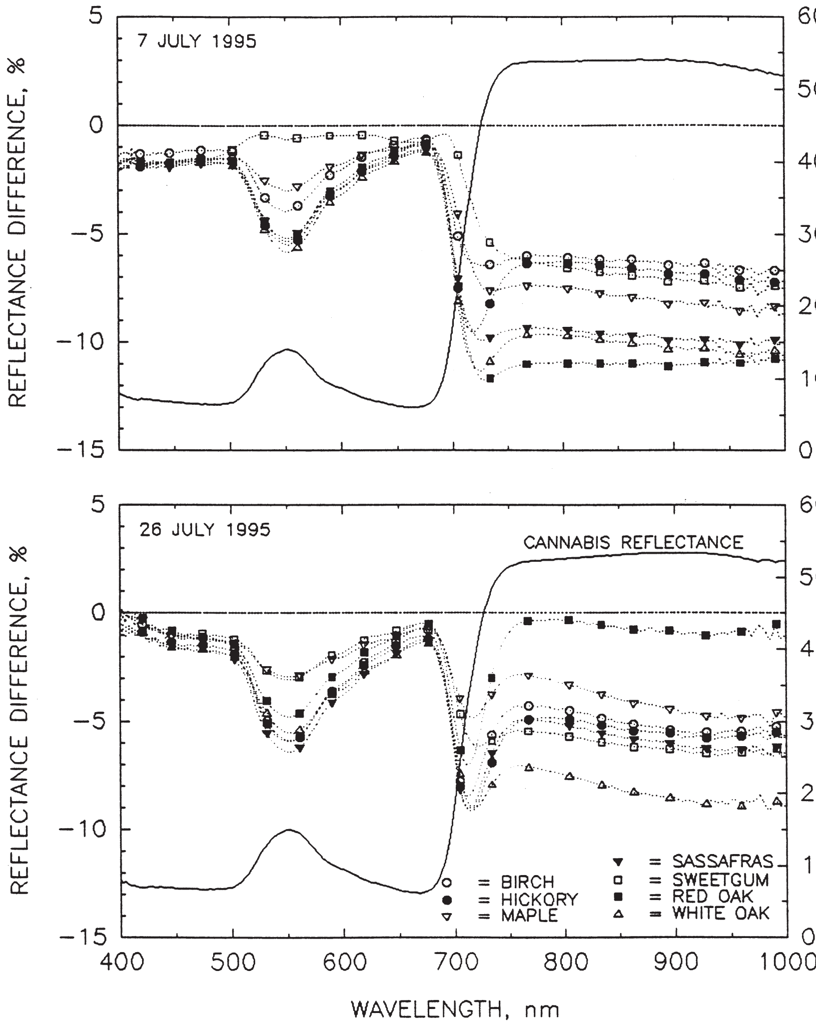


Figure 5. Differences in the reflectance spectra of the tree leaves from the reflectance spectra of Colombian marijuana leaves. The reflectance spectrum of marijuana leaves was subtracted from the reflectance spectrum of the tree leaves. The line at 0 indicates no change from the reflectance of marijuana. The reflectance spectrum for marijuana is also shown.

were identical, RMSD would be zero. The greater the value of RMSD, the more dissimilar are the spectra. We separated the corn spectra from the other herbaceous species spectra because of the differences noted previously. In the visible wavelengths, a broad RMSD maximum occurred near 550 nm (green region) and a minimum RMSD near 670 nm (red region) in all species. In all cases, the RMSD increased as a function of wavelength from 750 to 1000 nm. The cannabis line of Figure 7 represents the deviations of N-deficient marijuana spectra from the spectra of well-fertilized marijuana. The RMSD values are large in the green (550 nm) and "red edge" (720 nm) regions of the spectrum, but are small in the red (670 nm) and near-infrared (>820 nm).

Simulated Canopy Reflectance

Reflectance of the dry Barnes soil (LAI=0 in Fig. 8A) was much lower at all wavelengths than the reflectance of the dry Othello soil (LAI=0 in Fig. 8B). These two soils provided highly contrasting backgrounds conditions for simulating the reflectance of plant canopies. The reflectance of the weathered crop residue (not shown) was intermediate between the soils. The reflectance spectra in Figure 8 are for the simulated marijuana canopies with LAI ranging from 0 to 8. In all cases, as LAI increased, reflectance in the visible decreased rapidly and approached its minima at LAI≥2. In contrast, reflectance in the near infrared increased and asymptotically approached its maxima at LAI≥6. Similar results have been widely reported for measured and modeled plants canopies (Gausman and Allen, 1973; Knipling, 1970; Bauer, 1975; Goel, 1989). The reflectance spectra of the other species are similar in overall appearance, but are not shown.

The residual canopy reflectance spectra were calculated by subtracting the marijuana canopy spectra (Fig. 8) from the canopy reflectance spectra of each species for corresponding levels of LAI (Fig. 9). Major deviations from the marijuana canopy reflectance spectra occurred at 550 nm, 720 nm, and 800 nm with minima at 670 nm and approximately 750 nm. As LAI increased, the deviations from the marijuana spectra increased as leaf spectral properties dominated the canopy reflectance (Fig. 9). At LAI<2, the deviations in canopy reflectance were

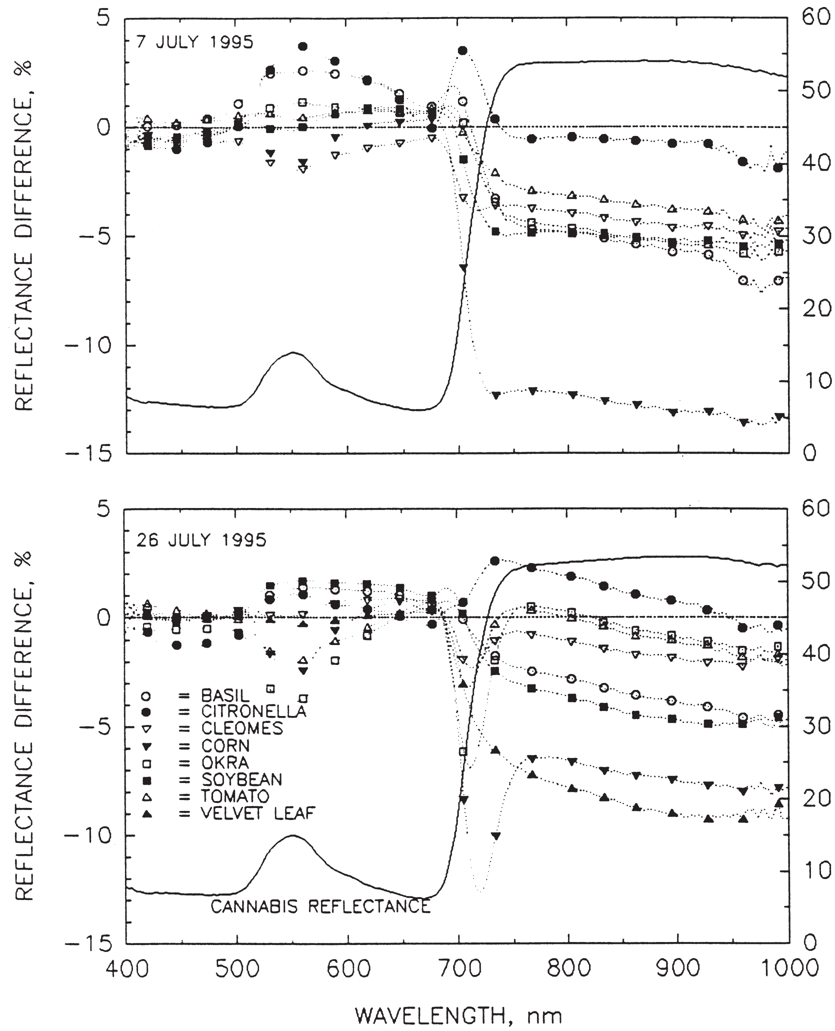
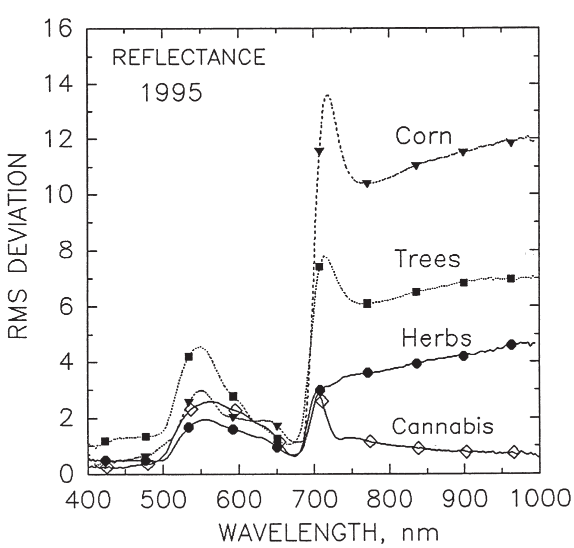


Figure 6. Differences in the reflectance spectra of the herbaceous plants from the reflectance spectra of Colombian marijuana leaves. The reflectance spectrum of marijuana leaves was subtracted from the reflectance spectrum of the other plant leaves. The line at 0 indicates no change from the reflectance of marijuana. The reflectance spectrum for marijuana is also shown.

Figure 7. Root mean deviations of the reflectance spectra of trees, herbs, and corn from the spectrum of Colombian marijuana. The data are averages for all dates in 1995.



small. Thus, dense canopies of marijuana may be more spectrally discriminable than sparse canopies.

In cases where marijuana and the surrounding vegetation have different LAIs, the deviations in reflectance spectral were greater than for the equal LAI case. Thus, well-fertilized and well-watered marijuana surrounded by natural vegetation should be readily distinguished by remote sensing.

CONCLUSIONS

Adaxial surface reflectance of marijuana leaves exhibited the typical healthy green leaf spectral signature of low visible reflectance and high near-infrared reflectance. No unusual or distinctive spectral features were evident when the data were presented as reflectance. Leaf transmittance also showed no surprises. Seasonal changes in leaf reflectance showed a progressive increase in visible reflectance of the 400–700 nm wavelength region. From 700–1000 nm the trends were less clear. Transmittance differences over the visible region changed from a generally positive difference to a negative difference as the

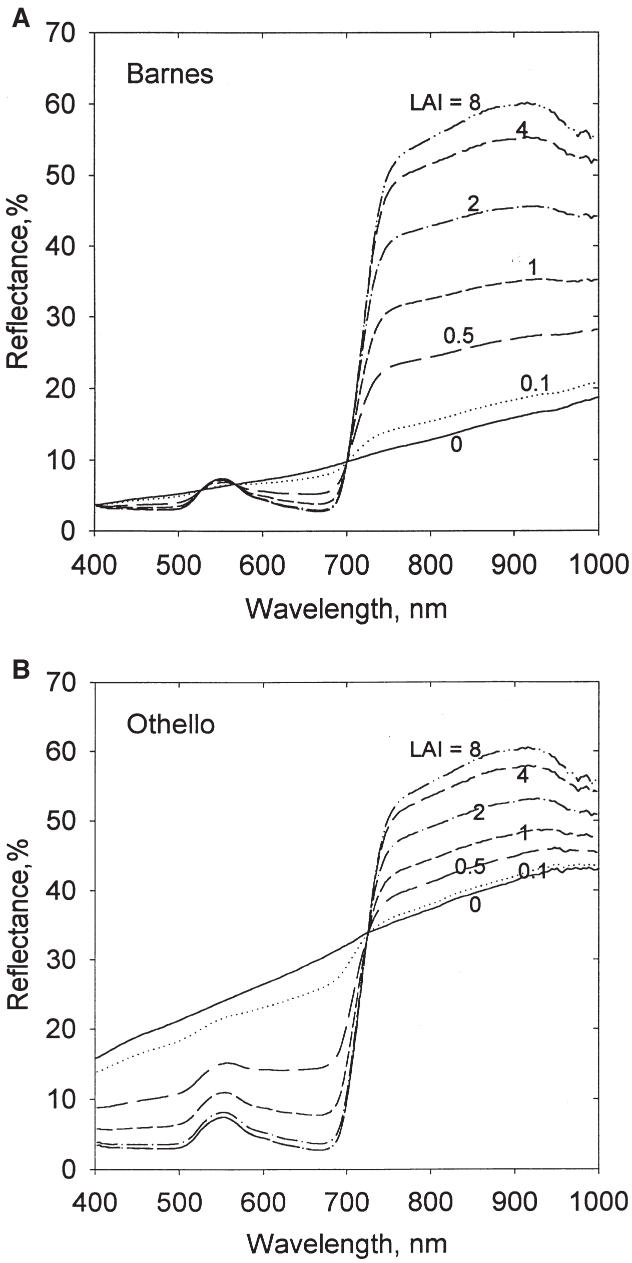


Figure 8. Simulated canopy reflectance spectra of marijuana on A) Barnes and B) Othello soils. LAI values displayed are 0, 0.1, 0.5, 1, 2, 4, and 8.

season progressed. Near-infrared transmittance showed an increasing negative difference over time. The magnitude of the differences were greater for transmittance than for reflectance. N-fertilization effects were evident in spectra of the marijuana leaves. The magnitude of the spectral differences between N-treatments varied over time with most differences occurring in the visible wavelength region. Lower N-treatments tended to have a higher visible reflectance.

The different marijuana selections had reflectance differences of less than 5%. The greatest differences

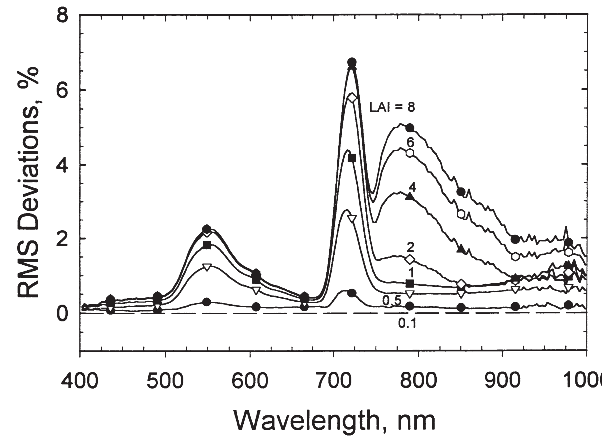


Figure 9. Root mean square deviations of canopy reflectance of selected species from the reflectance of marijuana at a series of LAI values. The data are means for five species and three backgrounds ($n=15$). LAI values displayed are 0.1, 0.5, 1, 2, 4, 6, and 8.

were in the 550 nm and 720 nm wavelength regions. Spectral differences between marijuana and tree species were larger than the differences between marijuana and other herbaceous species. Again, the greatest differences were near 550 nm and 720 nm. The "red edge" region near 720 nm warrants further investigation. It may be possible to exploit reflectances differences in the slope of the red to near-infrared transition for species discrimination.

Canopy reflectance spectra of marijuana and several representative species were simulated for a wide range of LAI and background reflectances. Major differences in canopy reflectance of marijuana and other plants were observed near 550 nm, 720 nm, and 800 nm. Dense canopies of marijuana were more spectrally discriminable from other vegetation than sparse canopies. Thus, based on measured leaf spectra and simulated canopy reflectance spectra, we would choose several relatively narrow (i.e., 30 nm or less) spectral bands in the green (550 nm), red (670 nm), "red edge" (720 nm), and the near-infrared (800 nm) to discriminate marijuana leaves and canopies from other species. Much of the leaf spectral information is available in the canopy reflectance data. The key issue is how to extract the required information from remotely sensed data that contains natural variability and noise introduced by the atmosphere and the sensor. In subsequent analysis, we will address some of these issues by characterizing and modeling the reflectance of plant canopies with different illumination and viewing conditions. This will allow a better evaluation of these bands for discriminating marijuana plants from other plants.

We gratefully acknowledge Andrew L. Russ and Pamela L. Nagler for their assistance with this experiment.

REFERENCES

Al-Abbas, A. H., Barr, R., Hall, J. D., Crane, F. L., and Baumgardner, M. F. (1974), Spectra of normal and nutrient-deficient maize leaves. *Agronomy J.* 66:16–20.

Bauer, M. E. (1975), The role of remote sensing in determining the distribution and yield of crops. *Adv. Agron.* 27:271–304.

Blackmer, T. M., Schepers, J. S., and Varvet, G. E. (1994), Light reflectance compared with other nitrogen stress measurements in corn leaves. *Agron. J.* 86:934–938.

Clarke, R. C. (1981), *Marijuana Botany,* And/Or Press, Berkeley, CA.

Collins, W. (1978), Remote sensing of crop type and maturity. *Photogramm. Eng. Remote Sens.* 44:43–55.

Daughtry, C. S. T., and Biehl, L. L. (1985), Changes in spectral properties of detached birch leaves. *Remote Sens. Environ.* 17:281–289.

Daughtry, C. S. T., Ranson, K. J., and Biehl, L. L. (1989), A new technique to measure the spectral properties of conifer needles. *Remote Sens. Environ.* 27:81–91.

Daughtry, C. S. T., McMurtrey, J. E., III, Kim, M. S., and Chappelle, E. W. (1997), Estimating crop residue cover by blue fluorescence imaging. *Remote Sens. Environ.* 60:14–21.

Elvidge, C. D., and Chen, Z. (1995), Comparison of broad-band and narrow-band red and near-infrared vegetation indices. *Remote Sens. Environ.* 54:38–48.

Gates, D. M., Keegan, H. J., Schleter, J. C., and Weidner, V. R. (1965), Spectral properties of plants. *Appl. Opt.* 1: 11–20.

Gausman, H. W., and Allen, W. A. (1973), Optical parameters of leaves of 30 plants species. *Plant Physiol.* 52:57–62.

Gausman, H. W., Allen, W. A., and Cardenas, R. (1969), Reflectance of cotton leaves and their structure. *Remote Sens. Environ.* 1:19–22.

Gausman, H. W., Allen, W. A., Escobar, D. E., Rodrigues, Z. Z., and Carenas, R. (1971), Age effects of cotton leaves on light reflectance, transmittance, and absorptance and on water content and thickness. *Agron. J.* 63:465–469.

Gausman, H. W., Allen, W. A., Wiegand, C. L., Escobar, D. E., Rodriguez, R. R., and Richardson, A. J. (1973), The leaf mesophyll of twenty crops, their light spectra, and optical and geometrical parameters, Technical Bull. No. 1465, U. S. Dept. of Agriculture, Washington, D.C., 59 pp.

Goel, N. S. (1989), Inversion of canopy reflectance models for estimation of biophysical parameters from reflectance data. In *Theory and Applications of Optical Remote Sensing*, (G. Asrar, Ed.), Wiley, New York, pp. 205–251.

Grant, L. (1987), Diffuse and specular characteristics of leaf reflectance. *Remote Sens. Environ.* 22:309–322.

Grant, A. B., and Murtha, P. A. (1994), Estimation of foliar macro-nutrients and chlorophyll in Douglas fir seedlings by leaf reflectance. *Can. J. Remote Sens.* 20:102–115.

Horler, D. N. H., Dockray, M., and Barber, J. (1983), The red-edge of plant leaf reflectance. *Int. J. Remote Sens.* 4: 273–288.

Knipling, E. B. (1970), Physical and physiological basis for the reflectance of visible and near-infrared radiation from vegetation. *Remote Sens. Environ.* 1:155–159.

Lichtenthaler, H. K. (1987), Chlorophylls and carotenoids: pigments of photosynthetic biomembranes. *Methods Enzymol.* 148:350–382.

Rock, B. N., Hoshizaki, T., and Miller, J. R. (1988), Comparison of *in situ* and airborne spectral measurements of the blue shift associated with forest decline. *Remote Sens. Environ.* 24:109–127.

Thomas, J. R., and Oerther, G. F. (1972), Estimating nitrogen content of sweet pepper leaves by reflectance measurements. *Agron. J.* 64:11–13.

Verhoef, W. (1984), Light scattering by leaf layers with application to canopy reflectance modeling: the SAIL model. *Remote Sens. Environ.* 16:125–141.

Woolley, J. R. (1971), Reflectance and transmittance of light by leaves. *Plant Physiol.* 47:656–662.