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# Vegetation Canopy PAR Absorptance and NDVI: An Assessment for Ten Tree Species with the SAIL Model

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*The relation between the normalized difference vegetation index (NDVI) and the fraction of absorbed photosynthetically active radiation ( $f_{\text{APAR}}$ ) was examined for ten different forest types by using the scattering-from-arbitrarily-inclined-leaves (SAIL) radiative transfer model. Leaf reflectance and transmittance, twig reflectance, and background reflectance data were collected as part of field experiments whose sites contain species whose ranges cover a significant part of western and northern North America. This provides a sense of variations that occur at continental scales. Actual backgrounds of forests include litter and mosses; these materials did not fall along a soil line in red-near infrared reflectance space. The simulations indicated that, at low values of the leaf area index (LAI), the background reflectance had a significant effect on the canopy reflectance, although little effect on photosynthetically active radiation (PAR) absorption. At higher values of LAI, leaf optical properties were the factors that dominated canopy reflectance and NDVI. Variations in canopy reflectance due to leaf optical properties were large, but most species had similar reflectance patterns. Green leaf optical properties, among the species studied, had little effect on  $f_{\text{APAR}}$ . The presence of twigs in the canopy had a noticeable effect on canopy reflectance and absorption of PAR, but these effects were secondary to the effects of background and leaf optical properties. ©Elsevier Science Inc.*

## INTRODUCTION

The study of the biosphere requires the ability to make repeatable measurements of vegetation characteristics at global scales. Remote sensing from orbiting platforms offers one of the best methods to acquire these types of data through its ability to repeatably acquire consistent observations over large areas. Data from visible and near infrared wavelengths have been combined to produce spectral vegetation indices (SVIs), which have been shown to be related to biophysical variables such as leaf area index (LAI), biomass, canopy cover, and the fraction of photosynthetically active radiation absorbed by vegetation ( $f_{\text{APAR}}$ ).  $f_{\text{APAR}}$  has been shown to be an important input into models used to determine transpiration, net primary productivity, or crop yield—key factors in understanding the moisture and carbon balance of the biosphere.

The studies that established the relation between remote sensing measurements and  $f_{\text{APAR}}$  were performed at local scales and on vegetation with simple canopies such as grasses and crops (Daughtry et al., 1982; Demetriades-Shah et al., 1992; Hatfield et al., 1984; Kumar and Monteith, 1981; Walter-Shea et al., 1992). However, simulations of light interactions in plant canopies indicate that the form of the relation between a SVI and  $f_{\text{APAR}}$  varies with changes in the canopy architecture and in the optical properties of the canopy components and background (Asrar et al., 1992; Baret and Guyot, 1991; Choudhury, 1987; Goward and Huemmrich, 1992; Huemmrich and Goward, 1990; Roujean and Breon, 1995). If satellite data are to be used as a measuring tool to determine  $f_{\text{APAR}}$  over large areas, where there are differences in canopy characteristics, then an understanding of how canopy variations can affect the measurement of  $f_{\text{APAR}}$  must be developed.

We previously examined this problem by using the

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Table 1. Tree Species Studied and Their Ranges

Common Name	Scientific Name	Distribution
Red alder	<i>Alnus rubra</i>	From southeastern Alaska southeast to central California, and is locally found into northern Idaho
Oregon white oak	<i>Quercus garryana</i>	From southwestern British Columbia to central California in the coastal ranges and Sierra Nevada
Western hemlock	<i>Tsuga heterophylla</i>	From southern Alaska southeast along the Pacific coast to northwestern California, as well as inland from southeastern British Columbia south into the Rocky Mountains to northern Idaho and northwestern Montana
Douglas fir	<i>Pseudotsuga menzeisii</i>	From central British Columbia southward along the Pacific coast to central California; also found inland into the Rocky Mountains south to southeastern Arizona
Sitka spruce	<i>Picea sitchensis</i>	Along the Pacific coast from a northernmost point in southern Alaska and British Columbia to northwestern California
Ponderosa pine	<i>Pinus ponderosa</i>	From southern British Columbia east to southwestern North Dakota, south to Trans-Pecos, Texas, and west to southern California and northern Mexico
Western juniper	<i>Juniperus occidentalis</i>	From central and southeastern Washington south to southern California
Trembling aspen	<i>Populus tremuloides</i>	Across northern North America from Alaska to Newfoundland, south to Virginia, and in Rocky Mountains south to southern Arizona and northern Mexico
Black spruce	<i>Picea mariana</i>	Across North America near northern limit of trees from Alaska and British Columbia east to Labrador, south to northern New Jersey, and west to Minnesota
Jack pine	<i>Pinus banksiana</i>	From the Mackenzie River and Alberta, east to central Quebec and Nova Scotia, southwest to New Hampshire, and west to northern Indiana and Minnesota

scattering from arbitrarily inclined leaves (SAIL) model to perform a sensitivity analysis of the effects of different canopy characteristics on the relation between NDVI and  $f_{\text{APAR}}$  [(Goward and Huemmrich, 1992); for a description of the SAIL model, see Verhoef (1984) and Alexander (1983)]. In that study, sensitivity analyses were performed by varying each variable about a nominal value. In this paper, we address some outstanding issues from the previous analysis. Here, the SAIL input variables were measured values for several different vegetation types. The effects of twigs on canopy radiative transfer also are examined.

Ten forest species were studied; these species have geographic ranges covering much of northern and western North America, representing a range of canopy characteristics that may be observed at continental scales (see Table 1). For these species, data were collected on the spectral reflectance and transmittance of leaves, twig spectral reflectance, the reflectance of typical materials found under the canopy, and the proportion of leaves and twigs in branches.

The leaf and needle reflectance and transmittance values and the twig and background reflectance values were combined in the SAIL model to study the effects that these values have on canopy reflectance and absorption of radiation. SAIL models a horizontally continuous canopy and cannot simulate the effects of canopy clumping and shadows. These effects will be examined in another paper.

## DATA COLLECTION

The data used in this study came from two remote sensing field experiments: the Superior National Forest (SNF) study in Minnesota and the Oregon Transect Ecosystem Research (OTTER) study in Oregon. The forests

studied in these campaigns contained a range of temperate tree species and canopy structures.

OTTER had six study sites in west-central Oregon, established along a temperature-moisture gradient to provide a large variation in species composition and vegetation structure (Gholz, 1982; Peterson and Waring, 1994). Field campaigns were conducted throughout the growing season of 1990, with additional field work in the summer of 1991.

The dominant tree species found in the OTTER sites were used in this study. These species were: sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), red alder (*Alnus rubra*), Douglas fir (*Pseudotsuga menzeisii*), Oregon white oak (*Quercus garryana*), ponderosa pine (*Pinus ponderosa*), and western juniper (*Juniperus occidentalis*). The westernmost OTTER sites in the Coast Range were dominated by sitka spruce, western hemlock, and red alder. The sites within the Willamette Valley were dominated by Douglas fir, with Oregon white oak at the lower elevations. The drier easternmost OTTER sites in the rain shadow of the Cascade Mountains were dominated by ponderosa pine and western juniper. Table 1 provides the geographical ranges of these species. NDVI values observed from the advanced very high resolution radiometer (AVHRR) on the NOAA satellites shows the same range in values over the Oregon Transect as over all of North America (Goward et al., 1994a, 1994b).

Optical properties of the canopy components were measured by using a Spectron Engineering SE590 spectrometer (Spectron Engineering, Denver, CO). The SE590 measures spectral reflectance in 0.03- $\mu\text{m}$  bands with usable data between 0.38 and 1.00  $\mu\text{m}$  (Walter-Shea and Biehl, 1990). The background reflectance data collected in OTTER was described in Goward et al. (1994a).

In the laboratory, with a LiCor 1800-12 integrating sphere (LiCor Inc., Lincoln, NE), needle, leaf, and twig reflectance and transmittance were determined by using the Daughtry et al. (1989) methodology. Branch samples were collected and sent to Goddard Space Flight Center (GSFC) where measurements were made. Branches were collected from parts of the canopy that were illuminated by the sun. The clipped ends of the branches were wrapped in damp paper towels, and the branches were chilled and then express mailed to GSFC where they were refrigerated until the measurements were made. Measurements were made within 2 days of the receipt of the branches. Because the purpose of these measurements was to develop branch-level reflectances, there was no separation between first-year growth and older growth. The optical property data are the mean values of eight scans of three samples. The spectra collected for the three samples were averaged together and broadband reflectance and transmittance values for red and near infrared were calculated by taking an average of all bands falling between 0.63 and 0.69  $\mu\text{m}$  for red and between 0.76 and 0.90  $\mu\text{m}$  for near infrared.

The relative areas of needles or leaves and twigs in branch samples were measured for four tree species, using the LiCor LI-3100 (Daughtry, 1990). Branch samples from OTTER that were not used for optical property measurements were measured. The branches measured were between 35 and 45 cm long. All needles or leaves were removed from the branch samples, and their one-sided cross-sectional area was measured. Owing to limitations in the amount of sample material, branch samples from only four species were measured: white oak, Douglas fir, ponderosa pine, and juniper. These values were assigned to the other species in the model parametrization. For example, the leaf to twig area ratio for white oak was used for all deciduous species.

NASA conducted field campaigns in the SNF during the summers of 1983 and 1984 (Hall et al., 1992b). The purpose of this study was to examine the use of remote sensing to collect information on key ecological variables in the boreal forest, such as LAI, biomass, and net primary productivity (Badhwar et al., 1986). The SNF is in northeastern Minnesota, north of the town of Ely, near the southern edge of the North American boreal forests. The study sites were dominated by trembling aspen (*Populus tremuloides*), black spruce (*Picea mariana*), or jack pine (*Pinus banksiana*).

High spectral resolution reflectance and transmittance measurements of leaves and needles between the wavelengths 0.35 and 2.1  $\mu\text{m}$  were collected for canopy components, using the Cary-14 laboratory spectrometer. The sampling interval varies between 0.002 and 0.01  $\mu\text{m}$ , depending on the rate of change in the measured optical property with wavelength. Cary-14 reflectance measurements were also made for bark samples, sphagnum moss,

and leaf litter. Data from a single spectrum of litter and sphagnum moss each were used. Branch samples were collected in the field and mailed to the laboratory at Johnson Space Center (JSC). For broad leaf samples, a leaf without holes or visible defects was used. For needle leaves, the needles were carefully aligned in the instrument holder to fill in any gaps (Hall et al., 1992b). This method of measuring needle optical properties may result in some errors (Daughtry et al., 1989). Gaps in these needle collections allow light to pass through the sample and will not be accounted for in the reflectance or transmittance calculation. Also, packing the needles closely together may allow multiple scattering between the needles to occur. These errors may be small if care has been taken in the arrangement of the needles. Fourteen leaf samples from several stand densities and canopy heights were used for the average aspen spectra. For black spruce, five samples were used for the needle reflectance average, and four samples were used for the needle transmittance average. In the spruce measurements, tops and bottoms of needles were mixed. For jack pine, only one sample was measured.

Bark reflectance spectra also were collected in the SNF study. One spectrum of aspen bark reflectance was used here; it comes from a branch from the upper part of the aspen canopy. Neither spruce nor jack pine twigs were measured in the SNF study. To fill in this data gap, the twig reflectances for Norway spruce and red pine read off of plots from Williams (1989) were used. As with the OTTER spectra, broadband reflectance and transmittance values were calculated as an average of all bands falling between 0.63 and 0.69  $\mu\text{m}$  for red and between 0.76 and 0.90  $\mu\text{m}$  for near infrared.

## OPTICAL PROPERTY RESULTS

Leaf-level red and near infrared reflectance and transmittance data for the ten forest species are listed in Tables 2 and 3. Leaf top refers to the upper side of the leaf as it is generally found oriented in the canopy. Reference to leaf top or leaf bottom in discussing reflectance or transmittance indicates the side of the leaf that is being illuminated in the integration sphere. Among the species measured from OTTER, the ponderosa pine and juniper needles did not have distinguishable tops and bottoms. In the SNF data, the black spruce needle measurements were of mixed needle tops and bottoms, and the jack pine needles did not have distinct tops and bottoms.

These ten species showed a range of leaf-top red reflectances between 0.047, for western hemlock, and 0.143, for juniper. In the near infrared, the leaf-top reflectances ranged from a low of 0.436 for juniper to a high of 0.567 for ponderosa pine. For leaf-top transmission in the red wavelengths, the values ranged from

Table 2. The Mean and Standard Deviation of Red and Near Infrared Leaf- and Needle-Top Reflectance and Transmittance

<i>Species</i>	<i>Red Reflectance Mean</i>	<i>Red Reflectance Standard Deviation</i>	<i>Near Infrared Reflectance Mean</i>	<i>Near Infrared Reflectance Standard Deviation</i>	<i>Number of Samples</i>
Alder	0.0781	0.0107	0.5111	0.0168	3
White oak	0.0604	0.0070	0.4831	0.0143	3
Douglas fir	0.0616	0.0117	0.5009	0.0461	3
Hemlock	0.0475	0.0092	0.5153	0.0084	3
Sitka spruce	0.0500	0.0088	0.4673	0.0373	3
Ponderosa pine	0.0916	0.0106	0.5686	0.0308	3
Juniper	0.1431	0.0135	0.4360	0.0694	3
Aspen	0.0700	0.0100	0.5053	0.0259	14
Black spruce	0.0974	0.0256	0.4680	0.0432	5
Jack pine	0.0536	0.0151	0.4522	0.0881	1

<i>Species</i>	<i>Red Transmittance Mean</i>	<i>Red Transmittance Standard Deviation</i>	<i>Near Infrared Transmittance Mean</i>	<i>Near Infrared Transmittance Standard Deviation</i>	<i>Number of Samples</i>
Alder	0.0110	0.0072	0.3938	0.0213	3
White oak	0.0062	0.0054	0.3451	0.0257	3
Douglas fir	0.0259	0.0068	0.3462	0.0245	3
Hemlock	0.0361	0.0127	0.4162	0.0077	3
Sitka spruce	0.0453	0.0149	0.4295	0.0112	3
Ponderosa pine	0.0356	0.0047	0.3157	0.0179	3
Juniper	0.0132	0.0015	0.1135	0.0127	3
Aspen	0.0318	0.0114	0.4072	0.0533	14
Black spruce	0.0221	0.0116	0.3857	0.0175	4
Jack pine	0.0049	0.0020	0.3340	0.0049	1

Table 3. The Mean and Standard Deviation of Red and Near Infrared Leaf- and Needle-bottom Reflectance and Transmittance

<i>Species</i>	<i>Red Reflectance Mean</i>	<i>Red Reflectance Standard Deviation</i>	<i>Near Infrared Reflectance Mean</i>	<i>Near Infrared Reflectance Standard Deviation</i>	<i>Number of Samples</i>
Alder	0.1648	0.0132	0.5188	0.0177	3
White oak	0.1362	0.0158	0.4847	0.0160	3
Douglas fir	0.1058	0.0335	0.5091	0.0590	3
Hemlock	0.1981	0.0181	0.5224	0.0056	3
Sitka spruce	0.1368	0.0181	0.4394	0.0361	3
Ponderosa pine					
Juniper					
Aspen	0.1385	0.0190	0.5133	0.0230	14
Black spruce					
Jack pine					

<i>Species</i>	<i>Red Transmittance Mean</i>	<i>Red Transmittance Standard Deviation</i>	<i>Near Infrared Transmittance Mean</i>	<i>Near Infrared Transmittance Standard Deviation</i>	<i>Number of Samples</i>
Alder	0.0088	0.0062	0.4062	0.0211	3
White oak	0.0043	0.0048	0.3476	0.0249	3
Douglas fir	0.0345	0.0058	0.3573	0.0110	3
Hemlock	0.0406	0.0112	0.4233	0.0059	3
Sitka spruce	0.0315	0.0139	0.4365	0.0136	3
Ponderosa pine					
Juniper					
Aspen	0.0327	0.0106	0.4119	0.0518	14
Black spruce					
Jack pine					

Table 4. The Mean and Standard Deviation of Red and Near Infrared Twig Reflectance

<i>Species</i>	<i>Red Reflectance Mean</i>	<i>Red Reflectance Standard Deviation</i>	<i>Near Infrared Reflectance Mean</i>	<i>Near Infrared Reflectance Standard Deviation</i>	<i>Number of Samples</i>
Alder	0.0939	0.0168	0.5761	0.0220	3
White oak	0.1239	0.0370	0.4164	0.1212	3
Douglas fir	0.1380	0.0242	0.5440	0.0217	3
Hemlock	0.1969	0.0546	0.4039	0.0458	3
Sitka spruce	0.2086	0.0424	0.4350	0.0934	3
Ponderosa pine	0.0991	0.0176	0.2516	0.0343	3
Juniper	0.2528	0.0261	0.4868	0.0506	3
Aspen	0.2453	0.0791	0.6766	0.0490	1
Norway spruce	0.3200		0.5500		Est.
Red pine	0.2700		0.4500		Est.

0.005 for jack pine to 0.045 for sitka spruce. In the near infrared wavelengths, leaf-top transmission ranged from 0.113 for juniper to 0.429 for sitka spruce. In comparing the data in Tables 2 and 3, note that the near infrared reflectances and transmittances for the leaf tops and bottoms were nearly identical. For the red wavelengths, the transmittance also was nearly the same for the leaf tops and bottoms. However, the leaf-bottom red reflectance was significantly higher in all cases than the leaf-top reflectance. A possible explanation of this characteristic is that the bright background allows photons that have traveled through the leaves, but have not been absorbed by chloroplasts, to be retained in the leaf by being reflected off the bright underside of the leaf. Photons that would otherwise be lost to the leaf may be absorbed by the chloroplasts (Lee, 1986).

The leaf and needle reflectance and transmittance data showed little clear-cut biogeographical trends in their characteristics. Some increase in the red reflectance of the ponderosa pine and juniper could be seen. Because these were plants found in the drier and sunnier sites, this may be an adaptation for keeping down the heat load of the needles. The work of Williams (1989) suggests that black spruce needle absorption in the near infrared is higher than in other conifers. This was proposed as a mechanism to help keep the needle clusters

warmer, allowing black spruce to survive in colder climates. In these data, black spruce needles did not have the highest near infrared absorption. Juniper, jack pine, and Douglas fir all had near infrared absorptances greater than that of black spruce, with juniper having needle absorption more than twice as great as black spruce.

These data indicated that leaf and needle optical properties varied between species and that the variation may not be predictable on the basis of a simple model using climate.

Twig reflectance values are listed in Table 4. The parts of the twigs measured were at the outer ends of the branches, which is the part of the branch most likely to be illuminated by the sun and seen by an overhead sensor. These data showed that there was a wide range in branch reflectance values. Red reflectances ranged from a low of 0.094 for red alder to a high of 0.32 for Norway spruce. Near infrared reflectances can be much greater than those for green leaves, with values ranging from 0.252 for ponderosa pine to 0.677 for aspen. Note that, even though the twig near infrared reflectance was large, the transmittance is zero. This means that, in the near infrared wavelengths, twigs are significant absorbers.

Table 5. Proportions of Leaf and Twig Area in Branches Used in This Study

<i>Species</i>	<i>Leaf Area to Twig Area Ratio</i>	<i>Fraction Leaves</i>	<i>Fraction Twigs</i>	<i>Source</i>
White oak	42.30	0.9769	0.0231	Measured
Douglas fir	9.74	0.9069	0.0931	Measured
Ponderosa pine	22.90	0.9582	0.0418	Measured
Juniper	8.63	0.8962	0.1038	Measured
Alder	42.30	0.9769	0.0231	Assigned
Hemlock	9.74	0.9069	0.0931	Assigned
Sitka spruce	9.74	0.9069	0.0931	Assigned
Aspen	42.30	0.9769	0.0231	Assigned
Black spruce	8.63	0.8962	0.1038	Assigned
Jack pine	8.63	0.8962	0.1038	Assigned

## BRANCH LEAF AND TWIG AREAS

The measured values for the leaf to twig area ratios, shown in Table 5, vary from a low of 8.63 for juniper to a high of 42.30 for white oak. When this is converted into the fraction of twigs per total plant area, twigs represent between 2% and 10% of the total branch area. The lack of data makes it difficult to generalize trends about the areas of leaves and twigs in branches. In these data, no clear trend between the drier and moister sites can be observed. Douglas fir found on the moist western side of the Cascade Mountains and juniper in the high desert both have nearly the same leaf to twig area ratios, and ponderosa pine, also from a drier site, has a value between those of the other conifers and the oak.

## BACKGROUND REFLECTANCE RESULTS

The broadband red and near infrared reflectances for the backgrounds for the OTTER and SNF sites are presented in Table 6. Also included in these data are in situ reflectance measurements of rabbitbrush (*Chrysothamnus viscidiflorus*) collected at the Metolius site and labeled Metolius brush. There can be a large range in reflectance values for different types of backgrounds. Red reflectance ranged from a low of 0.065 for litter at Corvallis to a high of 0.253 for bare soil at the Juniper site. Near infrared reflectance also was lowest at the Corvallis site, at 0.1287, and highest at the Juniper site, at 0.3228. For all of the litter reflectances (Cascade Head, Corvallis, Scio, and SNF aspen litter), the red reflectance was consistently about half the near infrared reflectance. The bare soils of the Metolius and juniper sites had red reflectances that were much greater relative to the near infrared reflectance. The sphagnum reflectance was very different from either the soils or the litter, having a typical green-plant reflectance pattern. In the open Metolius site, the layer of brush might be considered the background of the ponderosa pine forest. The addition of the rabbitbrush over the Metolius soil slightly increased the red reflectance and nearly tripled the near infrared reflectance. Although litter red and near infrared reflectances in this data set seem consistent in their propor-

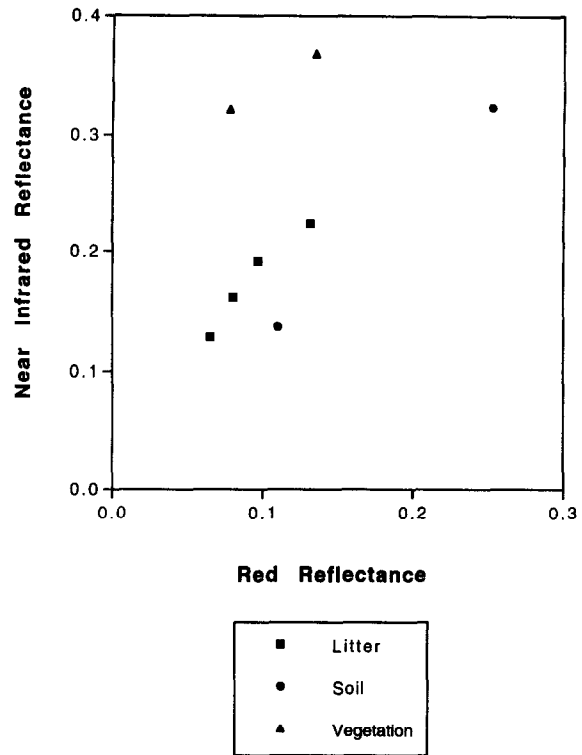


Figure 1. Red and near infrared reflectances of background materials.

tions, the soils were very different, as were the green backgrounds of moss or brush. A consistent soil line in spectral space did not occur in this data set for the collection of backgrounds observed. This can be seen in Figure 1, where the three different types of backgrounds are displayed in red–near infrared reflectance space.

## SAIL MODEL CALCULATIONS

SAIL model simulations of canopy reflectances used a combination of the data acquired in this study and the baseline data set described in Goward and Huemmrich (1992) and shown in Table 7. The effects of each variable were examined separately with the use of baseline values for all other parameters, with LAI varying through

Table 6. The Mean and Standard Deviation of Red and Near Infrared Background Reflectance

Species	Red Reflectance Mean	Red Reflectance Standard Deviation	Near Infrared Reflectance Mean	Near Infrared Reflectance Standard Deviation	Number of Samples
Cascade Head litter	0.0962	0.0116	0.1925	0.0257	10
Warning's Woods litter	0.0651	0.0131	0.1287	0.0260	10
Scio litter	0.0799	0.0157	0.1625	0.0290	10
Metolius soil	0.1100	0.0168	0.1362	0.0125	10
Metolius brush	0.1351	0.0219	0.3675	0.0485	10
Juniper soil	0.2527	0.0351	0.3228	0.0427	10
SNF litter	0.1318	0.0101	0.2251	0.0183	1
SNF sphagnum	0.0782	0.0155	0.3214	0.0083	1

Table 7. Baseline Input Variables Used in SAIL Model Runs (Source: Goward and Huemmrich 1992; Williams 1989)

Illumination and Viewing Conditions:		
Latitude		40° N
Observation time (local solar time)		14:00
Solar declination angle		0° (equinox)
Solar zenith angle at observation time		48.44°
Sensor view zenith angle		0° (nadir)
Proportion of direct irradiance		1.0
Canopy Structure:		
Leaf inclination angle distribution		Spherical
Twig inclination angle distribution		Planophile
Plant area index values		0.01, 0.25, 0.50, 0.75, 1, 2, 3, 4, 5, 7
Canopy Optical Properties		
	<i>Red</i>	<i>Near Infrared</i>
Leaf reflectance	0.05	0.48
Leaf transmittance	0.05	0.48
Twig reflectance	0.30	0.60
Twig transmittance	0.00	0.00
Background reflectance	0.135	0.150

the values listed in Table 7, to generate the curves. This allowed an investigation of the importance of each component in determining canopy reflectance and  $f_{\text{APAR}}$  independently of the other variables. The method of calculating  $f_{\text{APAR}}$  from the SAIL model follows the procedure described in Goward and Huemmrich (1992). The  $f_{\text{APAR}}$  values used in this paper are instantaneous values calculated at the same solar zenith angle as that of the reflectance calculations.

## BACKGROUND EFFECTS

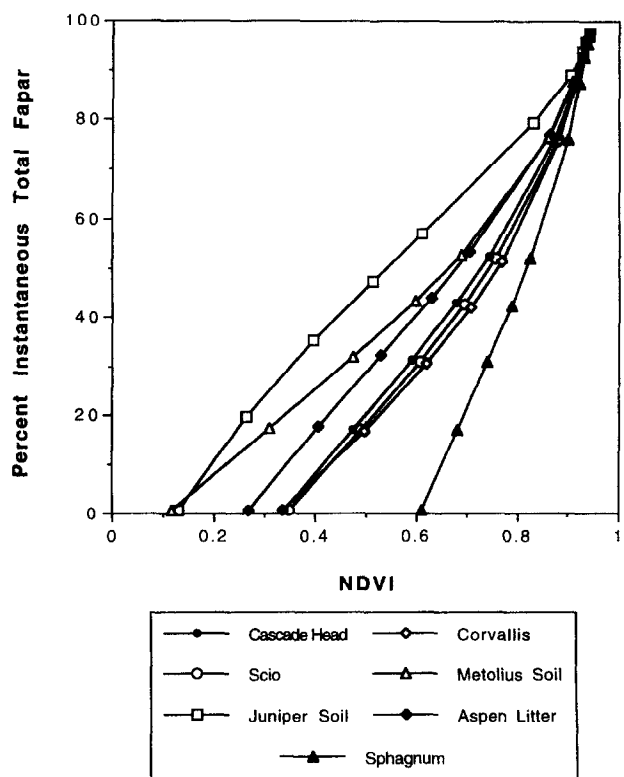
The SAIL model was used to describe a horizontally uniform canopy consisting only of leaves with no twigs, using baseline values for all variables except background reflectance. From the model output, NDVI and  $f_{\text{APAR}}$  were calculated, and the results are shown in Figure 2. The effects of background reflectance were dramatic. The range of possible  $f_{\text{APAR}}$  values for a given NDVI, if background was not known, could be as much as 50%. This was a greater range than we found in our earlier look at background reflectance effects (Goward and Huemmrich, 1992).

In Figure 2, the NDVI of the backgrounds alone (i.e., NDVI values when  $f_{\text{APAR}}$  is zero) fell into three groups: soils, litter, and vegetation, with soils having the lowest and vegetation having the highest NDVI. The  $f_{\text{APAR}}$  was calculated only for the canopy; it did not include photosynthetically active radiation (PAR) absorbed by any vegetation in the background. The spectral properties of the background did more than determine the lower end point of the NDVI- $f_{\text{APAR}}$  curve; it also affected the shapes of the curves. Note the difference in curvature between the Metolius soil and juniper soil curves in Figure 2. Both soils had nearly the same NDVI value, but the bright juniper soil produced a lower NDVI and a slightly higher  $f_{\text{APAR}}$  for a given LAI.

## EFFECTS OF LEAF OPTICS

To examine the effects of leaf optical properties, measured values of leaf or needle optical properties with baseline values for all other variables were used as inputs to the SAIL model. The canopy contains only leaves whose optical properties were described by the mea-

Figure 2. Instantaneous total  $f_{\text{APAR}}$  versus NDVI from SAIL model, using measured backgrounds and baseline leaf optical properties.





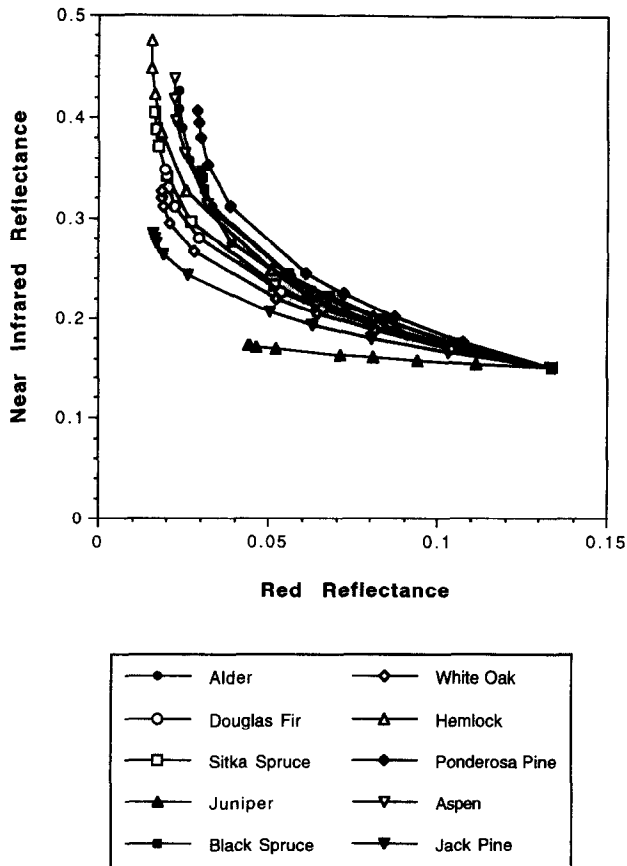


Figure 3. Near infrared and red reflectance from SAIL model, using measured leaf optical properties and baseline background reflectance.

sured leaf-top reflectance and transmittance values. As LAI increased, all canopies had a decrease in red reflectance and an increase in near infrared reflectance from the baseline background reflectance (Fig. 3). Of the leaf types shown here, juniper needles displayed the least increase in near infrared reflectance and the least decrease in red reflectance for a given value of LAI. At a LAI of 7, juniper had the highest red reflectance at 0.044 and the lowest near infrared reflectance with a value of 0.173. After juniper, the next highest red reflectance was black spruce at 0.030, and the next lowest near infrared reflectance was jack pine at 0.284. At the other extreme, for a LAI of 7, western hemlock had the highest near infrared reflectance at 0.476 and the lowest red reflectance at 0.015. This plot displays a large variation in canopy reflectance for canopies with the same LAI value. This variability in canopy reflectance properties can be useful in classification of vegetation types but presents a problem for remote sensing of biophysical variables.

In Figure 4, these model results are used to show the relation between NDVI and  $f_{\text{APAR}}$ . The general form of the relation between these two variables was the same for all leaves. The relation was generally linear up to a  $f_{\text{APAR}}$  value of approximately 0.75, followed by an upward curving with  $f_{\text{APAR}}$  increasing more rapidly than NDVI.

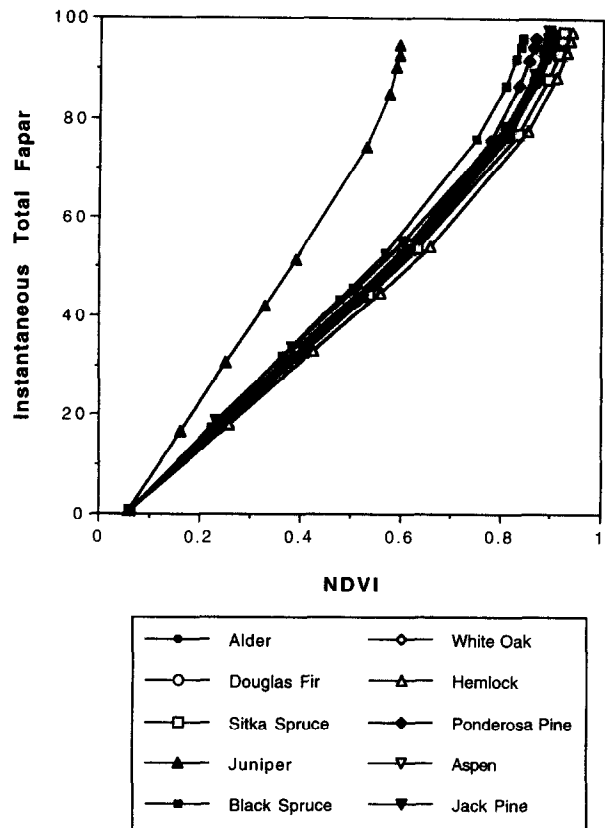


Figure 4. Instantaneous total  $f_{\text{APAR}}$  versus NDVI from SAIL model, using measured leaf optical properties and baseline background reflectance.

The slopes of the linear segments vary with the optical properties of the leaves. Despite the variability in canopy reflectances, except for juniper, the NDVI- $f_{\text{APAR}}$  relations were close together. At a LAI of 7, juniper had a NDVI of 0.595. Of the canopies that clump together in these curves, the lowest NDVI at a LAI of 7 was black spruce at 0.841, and the highest was western hemlock at 0.937. Although most of the curves appeared close together, because of the change in curvature at the upper ends of the curves, the range of possible  $f_{\text{APAR}}$  values for a value of NDVI may be as high as 20%, and, if the juniper curve is added, the range may extend to more than 45%.

## EFFECTS OF TWIGS IN THE CANOPY

A significant difference between herbaceous canopies and forests is the presence of twigs in forest canopies. SAIL model simulations were performed to examine the effects of mixtures of twigs and leaves in the canopy. The first simulation used the baseline input values and looked at varying proportions of twigs and leaves in similar canopies. Twigs had a planophile inclination angle distribution, and leaves had a spherical leaf angle distribution (Hutchison et al., 1986).

Figure 5 shows the trajectory of each canopy with different proportions of twigs and leaves in red-near in-

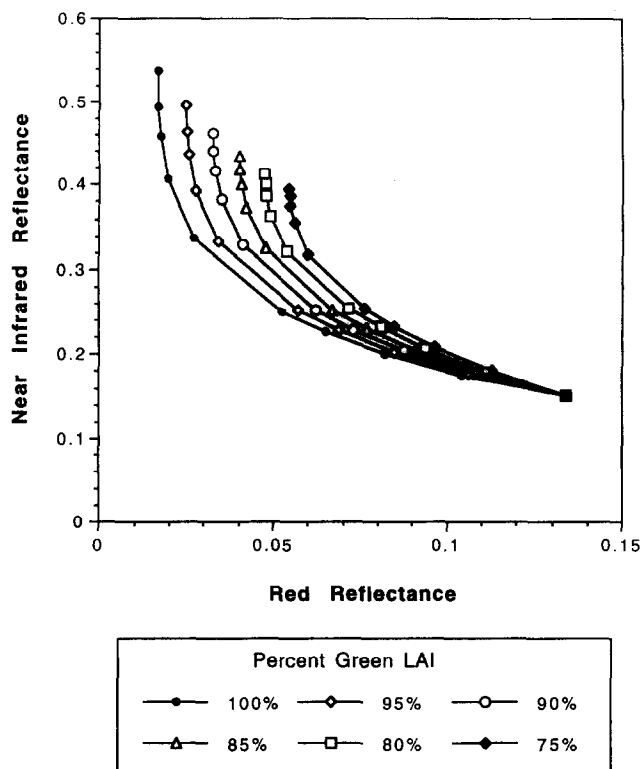


Figure 5. Near infrared and red reflectance from SAIL model for canopies containing varying proportions of leaves and twigs.

frared spectral space. In each curve, the total plant area index (the plant area index is the sum of the relative cross-sectional areas of the leaves and twigs per unit ground area) varied from 0.01 to 7. Corresponding points on each curve indicated the same plant area index value. All curves began at the same point—the background reflectance value. At plant area indices less than 2, variations in the proportion of twigs mainly affected the red reflectance. At higher plant area indices, twigs in the canopy also affected the near infrared reflectance. Even though the twigs had a high near infrared reflectance, they were significant absorbers in the near infrared, because they did not transmit any radiation. The presence of even small amounts of absorbers in a highly scattering medium may have a significant effect. Changing the canopy from all green leaves to 5% twigs at a plant area index of 7 lowered the near infrared reflectance by approximately 5% reflectance.

For deciduous trees, the ratio of leaf to twig area will vary throughout the growing season. The twig area varies little during the year, but the green-leaf area changes dramatically, increasing in the spring decreasing in the fall. In early spring, the leaf to twig ratio will be low, but it will increase into the summer and then decrease in the fall. Deciduous tree reflectance over a year is not represented by any single curve shown here; rather a deciduous

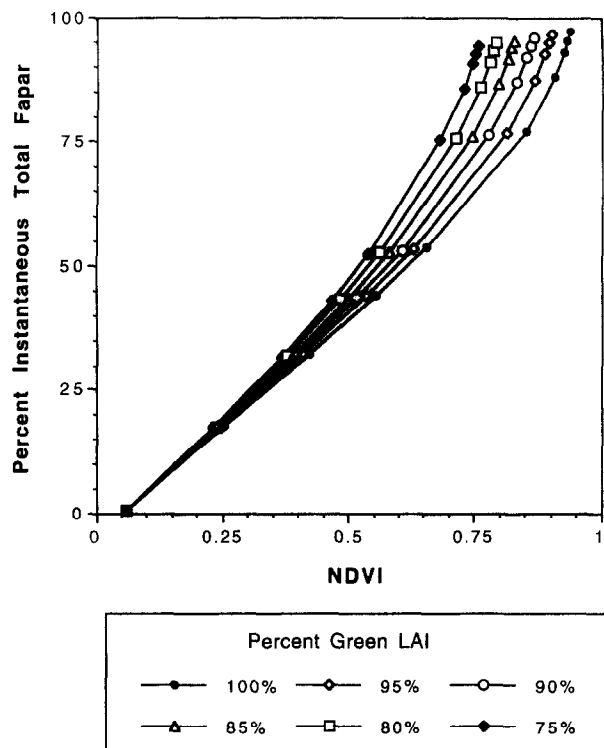


Figure 6. Instantaneous total  $f_{APAR}$  versus NDVI from SAIL model run for canopies containing varying proportions of twigs.

ous tree reflectance curve would cross through the range of curves presented in Figure 5.

Figure 6 shows the effect of twigs on the relation between NDVI and  $f_{APAR}$ . For a given plant area index, variations in the proportion of twigs mostly affected NDVI, rather than  $f_{APAR}$ . Similar results have been seen owing to the effects of senescent leaves mixed in a prairie grass canopy (Hall et al., 1992a). The largest differences in the estimate of  $f_{APAR}$  from a given value of NDVI are at the highest values of LAI. Over the range of values used in this example, the error in estimating  $f_{APAR}$  from NDVI could be as great as 30%  $f_{APAR}$ .

NDVI is determined by the difference between red and near infrared reflectances, so it is sensitive to the amount of illuminated green foliage in the canopy (Prince, 1991). In the prairie, Hall et al. (1992a) found that NDVI had the best relation with "green"  $f_{APAR}$ . Green  $f_{APAR}$  was defined as the product of the total  $f_{APAR}$  and the fraction of green biomass in the canopy. The green  $f_{APAR}$  was determined in these SAIL model simulations by multiplying the total  $f_{APAR}$  by the fraction of green LAI. Figure 7 shows that much of the differences in the relations between NDVI and total  $f_{APAR}$  collapsed together when green  $f_{APAR}$  was used. These results indicated that canopy spectral reflectances and total PAR absorption were affected by the presence of nongreen materials, such as twigs and dead leaves, in the canopy.

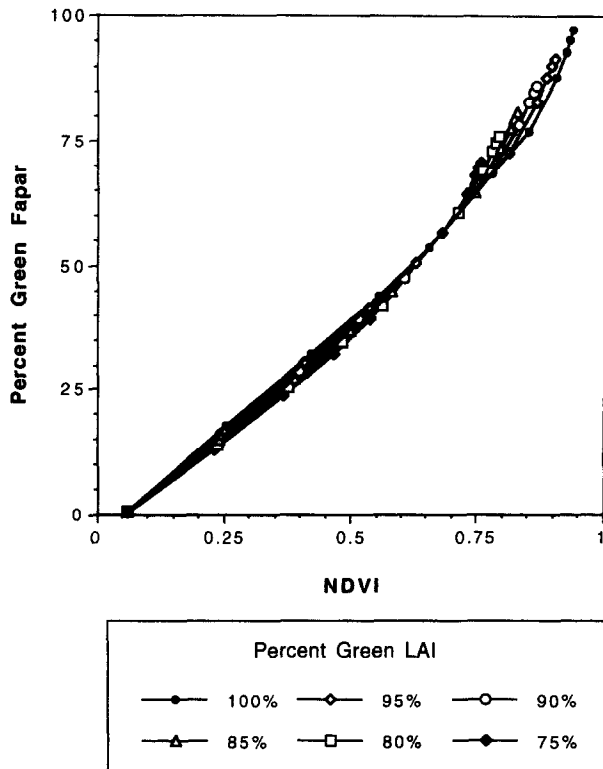


Figure 7. Instantaneous green  $f_{\text{APAR}}$  versus NDVI from SAIL model run for canopies containing varying proportions of twigs. Green  $f_{\text{APAR}}$  is the product of the total  $f_{\text{APAR}}$  and the fraction of green LAI.

However, NDVI appeared to continue to be sensitive to the fraction of incoming PAR absorbed by living foliage, which is the variable of interest in vegetation productivity models.

Twigs and other nongreen material in the canopy can have a significant effect on both the reflectance and the absorption of radiation in vegetation canopies. These model runs suggest that a SVI such as NDVI may minimize these effects by being sensitive only to green  $f_{\text{APAR}}$ . However, this also indicates that, in using a SVI, one must be clear about exactly what biophysical variable is being retrieved and how it is to be used. Green  $f_{\text{APAR}}$  is a useful variable for productivity studies. Green  $f_{\text{APAR}}$  would not be as useful for calculations of sensible heat flux of a canopy with a large amount of twigs in it, because then the variable of interest is the total energy absorbed by the canopy. There is currently no simple, non-destructive method of measuring green  $f_{\text{APAR}}$  in the field. All methods of measuring absorbed PAR in canopies measure total PAR absorption, and there is no practical direct method of separating the PAR absorbed by the green leaves from the total. Attempts to estimate the fractional area of twigs in the canopy have used ratios of transmitted red and near infrared light [(Jordan, 1969); J. Berry, personal communication]. Looking at the SAIL model red and near infrared transmittances for varying

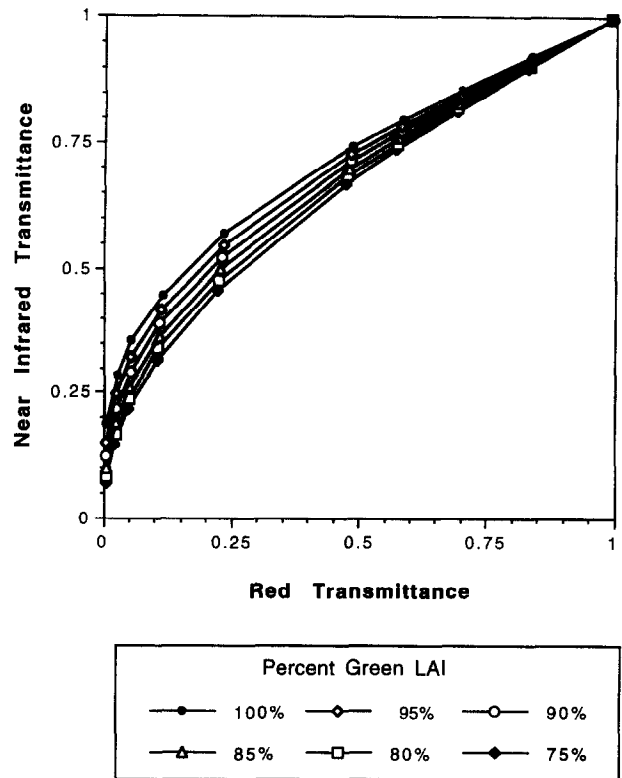


Figure 8. Near infrared and red transmittance from SAIL model for canopies containing varying proportions of leaves and twigs.

amounts of twigs in a canopy in Figure 8 reveals the problems in interpreting the transmittance data. The curved shape of the trajectories coupled with the small changes in the curves for changing fractions of twigs suggest that it is difficult to separate twig amounts from changes in overall plant area.

These simulations indicate that variations in the amount of twigs in canopies affect the relation between NDVI and total  $f_{\text{APAR}}$ . For a consistent set of leaf and twig optical properties, the relation between NDVI and green  $f_{\text{APAR}}$  varies little owing to differences in the amount of twigs in the canopy.

To examine the effects of twigs in different forest species, the model was parametrized by using the measured leaf and twig optical properties and proportions in the canopy. As in the previous simulation, twig transmittance was zero. Both components, leaves and twigs, were mixed in a single layer in the model. The leaves had a spherical inclination angle distribution, and the twigs had a planophile inclination angle distribution. The background reflectance was the baseline value. Plant area index varied from 0.01 to 7. The proportion of leaf area to twig area used for each tree species was held constant as plant area index varied. The relative leaf and twig areas used are shown in Table 5.

In Figure 9, the red and near infrared reflectances for canopies with twigs are plotted along the reflectances

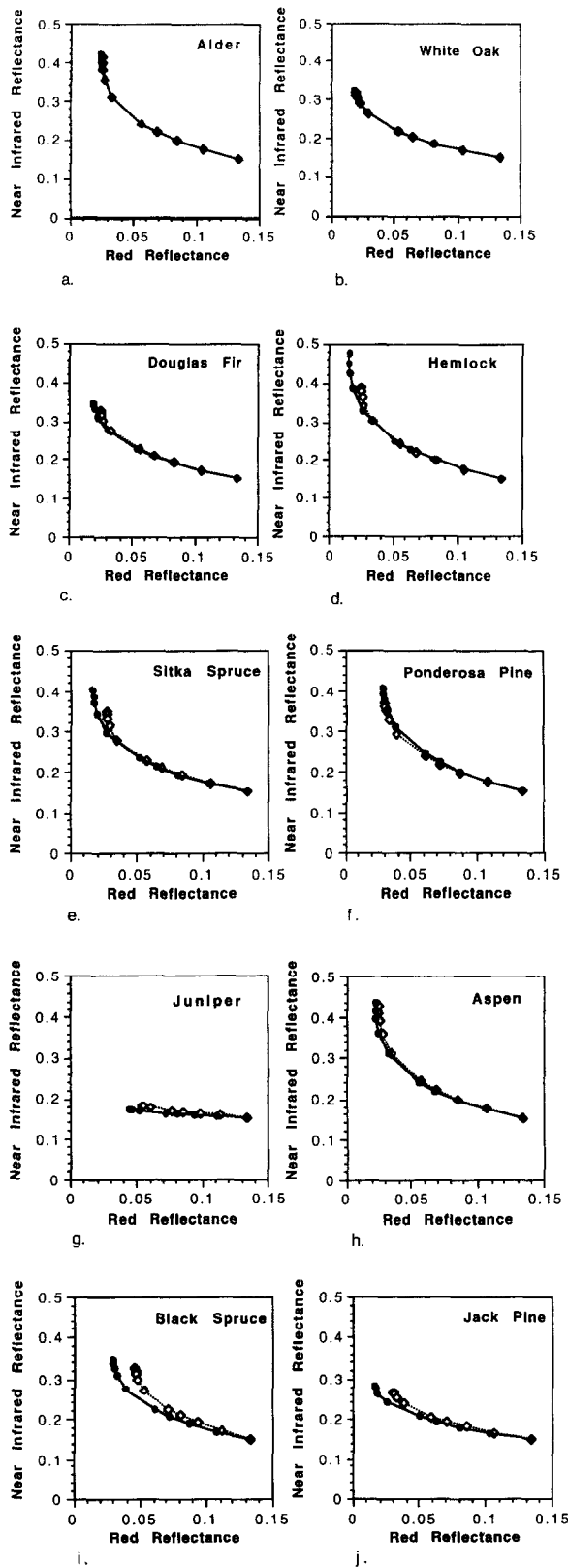


Figure 9. Near infrared and red reflectance from SAIL model for canopies with and without twigs in them, using baseline background and measured leaf and twig optical properties. Simulations for canopies without twigs are displayed by solid lines with filled points; canopies with twigs are shown by dotted lines with open diamonds.

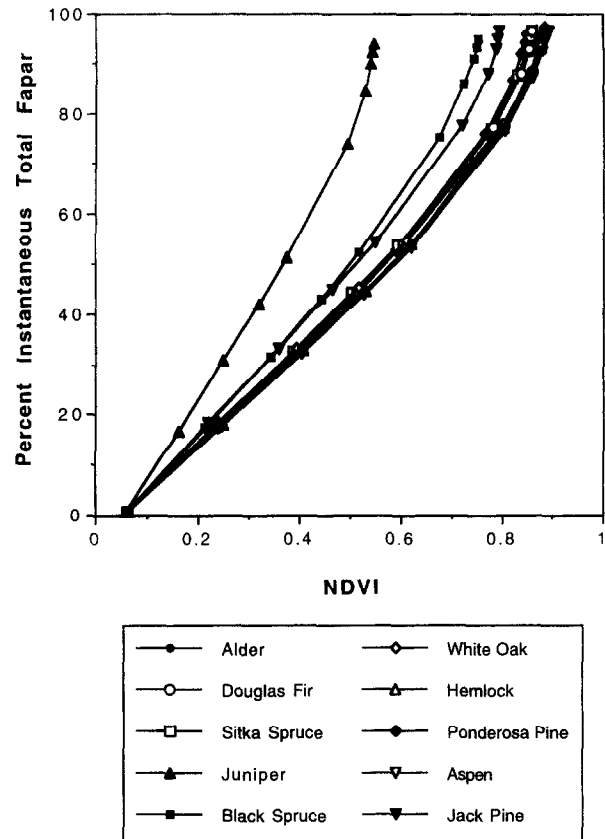


Figure 10. Instantaneous total  $f_{APAR}$  versus NDVI from SAIL model using measured leaf and twig optical properties and baseline background reflectance.

of canopies without twigs to examine the effects of twigs on canopy reflectance. The without-twig canopy reflectances were the same simulations displayed in Figure 3. For some species, such as alder and white oak, there was little difference in canopy reflectance with and without twigs [Fig. 9(a and b)]. Western hemlock showed approximately a 10% reflectance decrease in the near infrared band due to the presence of twigs in canopies with plant area indices of 7 [Fig. 9(d)]. Black spruce, though not showing a large difference in near infrared reflectance due to twigs, did have almost a 2% decrease in red reflectance for canopies with plant area indices of 7 [Fig. 9(i)].

As seen in the SAIL model runs presented in Figure 9, variations in canopy reflectance due to the presence of twigs in the canopy may be significant. However, the magnitude and nature of the differences in reflectance are not consistent. The effects of twigs on canopy reflectance depend on the proportion of twigs in the canopy as well as the optical properties of both the twigs and the leaves.

From these same simulations, NDVI and total  $f_{APAR}$  were calculated. These results are shown in Figure 10. A comparison of Figure 4, in which the canopies consist only of leaves, with Figure 10 shows that twigs in the canopy did not dramatically change the relation between

NDVI and  $f_{\text{APAR}}$ . There was little change in total  $f_{\text{APAR}}$  values in all canopies, with and without twigs. With twigs substituting for leaves in the canopies,  $f_{\text{APAR}}$  decreased slightly, but this decrease was little more than 1%. In all cases, there was a slight decrease in NDVI for the canopies containing twigs. Not surprisingly, the largest changes in NDVI occurred in the conifers with the largest proportion of twigs in the canopy. The broad-leaved trees showed little change in their NDVI values. Interestingly, for most of the species, the addition of twigs to the canopy reduced the between-species variations in the NDVI- $f_{\text{APAR}}$  relation. For species such as western hemlock, the leaf-only NDVI values were higher than the broadleaf NDVI for the same leaf area. With the addition of twigs in the canopy, the hemlock NDVI dropped, bringing its NDVI values closer to those of the broadleaf species. The exceptions to the general grouping were black spruce, jack pine, and juniper. For black spruce and jack pine, the decrease in NDVI caused by twigs in the canopy was the greatest of all the species examined here. At a plant area index of 7.0, black spruce NDVI decreased by 0.09 and jack pine decreased by as much as 0.1. The large decrease in NDVI for these species moved their curves away from the rest of the NDVI- $f_{\text{APAR}}$  relations. For the species that grouped together, the maximum range of total  $f_{\text{APAR}}$  values for a given NDVI was about 10%  $f_{\text{APAR}}$ . The addition of jack pine and black spruce to the population increased the maximum range of total  $f_{\text{APAR}}$  values to about 25%  $f_{\text{APAR}}$ ; including juniper raises this to more than 45%  $f_{\text{APAR}}$ .

### GREEN $f_{\text{APAR}}$

In canopies containing components other than green leaves, the total PAR absorbed by the canopy is the sum of the PAR absorbed by the green leaves and the PAR absorbed by the other components, such as twigs or dead leaves. The fraction of PAR absorbed by green leaves, or green  $f_{\text{APAR}}$ , is an important variable in the modeling of plant productivity or stomatal conductance. Earlier, green  $f_{\text{APAR}}$  was calculated by using the method of Hall et al. (1992a). That approach was based on the idea that the mass per unit leaf area of dried green and dead leaves was the same, that the green and dead leaves had the same leaf angle distribution, and that they were uniformly mixed in the canopy. However, in the previous simulations, the inclination angle distribution of the twigs differed from that of the leaves. In addition, between species, the leaves and twigs have different optical properties, which may affect PAR absorption. The SAIL model can be configured to explicitly separate the PAR absorbed by each component, testing the assumptions that have gone into calculating green  $f_{\text{APAR}}$ .

In all the previous SAIL simulations, the canopy modeled consisted of a single layer of vegetation. When there was more than one component in the canopy, the

Table 8. Fraction of  $F_{\text{APAR}}$  Absorbed by Green Leaves in Branches Calculated by Using the SAIL Model

Species	Fraction Green $f_{\text{APAR}}$	Fraction Leaf Area
Alder	0.9770	0.9769
White oak	0.9782	0.9769
Douglas fir	0.9112	0.9069
Hemlock	0.9173	0.9069
Sitka spruce	0.9175	0.9069
Ponderosa pine	0.9568	0.9582
Juniper	0.9069	0.8962
Aspen	0.9804	0.9769
Black spruce	0.9180	0.8962
Jack pine	0.9174	0.8962

components were randomly mixed together. This configuration made it impossible to separate green leaves from other components. The model can be reconfigured to allow this separation. SAIL simulations were set up with 30-layer canopies. Every other horizontal layer contained only leaves, and the alternate layers contained only branches. The radiation absorbed by each layer was calculated. Isolating each component into separate layers allowed the determination of the PAR absorbed by leaves and twigs separately. Having multiple layers enabled the vertical mixing of the components to approximate a single layer.

The model was executed for the same plant areas as those of the single-layer simulations with the values for the proportions of leaves and twigs from Table 5. In this case, the total leaf area was divided into 15 layers, as was the total twig area. This allows each layer to have a low component area, simulating a vertical mixture of the materials. As before, the leaves had a spherical leaf inclination angle distribution, and the twigs had a planophile inclination angle distribution. Total canopy  $f_{\text{APAR}}$  and red and near infrared reflectance were calculated, as well as  $f_{\text{APAR}}$  for the layers containing only green leaves. The multilayer canopy total  $f_{\text{APAR}}$  and canopy reflectances were identical with the values from the single-layer canopy runs to three figures. This indicates that the multilayer model was simulating a uniform vertical mixture of the different canopy components.

The multilayer SAIL model provided a means to separate the absorption of PAR by the green leaves and twigs. For the different plant area indices, the fraction of incoming PAR absorbed by the green-leaf layers was plotted against the total fraction of incoming PAR absorbed by the entire canopy. The points were fit with a linear regression. The slopes of the least-squares fit are listed in Table 8 along with the ratio of green leaf to total plant area used in the model runs. These results show that the fraction of green  $f_{\text{APAR}}$  was slightly greater than the fraction of green LAI, but the two values were within 1% of each other. The multilayer SAIL simulations indicated that the assumptions used by Hall et al.

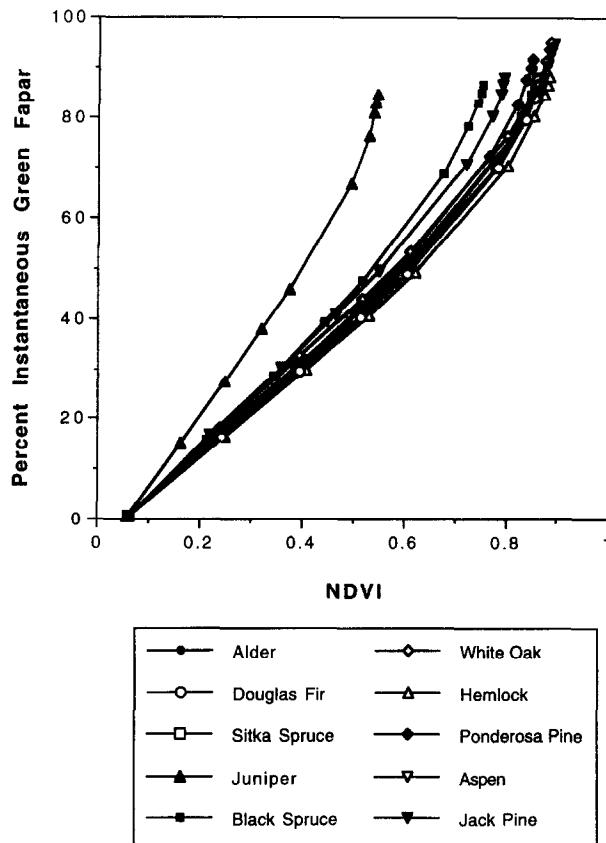


Figure 11. Instantaneous green  $f_{APAR}$  versus NDVI from SAIL model using measured leaf and twig optical properties and baseline background reflectance.

(1992a) provided reasonable field values for the fraction of green  $f_{APAR}$ .

Green  $f_{APAR}$  was calculated as the product of the fraction of green  $f_{APAR}$  and the total  $f_{APAR}$  values shown in Figure 10. The green  $f_{APAR}$  is plotted against NDVI in Figure 11. Green  $f_{APAR}$  was less than total  $f_{APAR}$  and therefore changed the slopes of linear parts of the relations. The variability in the estimate of green  $f_{APAR}$  from NDVI was little improved over the variability seen in the total  $f_{APAR}$ -NDVI relations. Hall et al. (1992a) suggested that the use of green  $f_{APAR}$  may significantly decrease the variability in the NDVI- $f_{APAR}$  relations developed from a single type of canopy made up of varying proportions of green leaves and nongreen materials (also see Fig. 7). These results indicated that, in cases with a variety of canopies, made up of leaves and twigs with different optical properties in each canopy type, the use of green  $f_{APAR}$  did not significantly reduce the variation in the NDVI- $f_{APAR}$  relations.

### COMBINING ALL MEASUREMENTS

All of the measured leaf and needle reflectance and transmittance data, background reflectance data, and branch level leaf and twig proportion data were combined in the next set of SAIL simulations. In these runs,

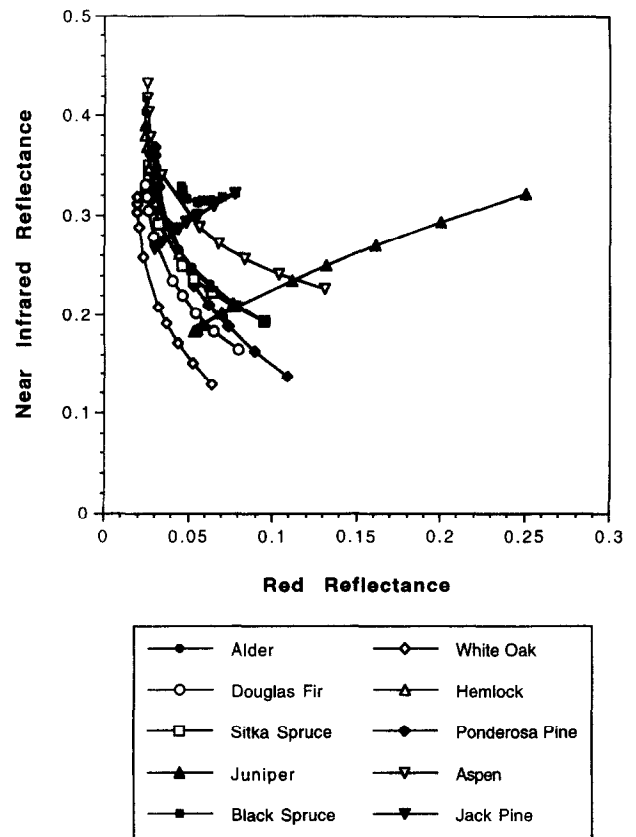


Figure 12. Near infrared versus red reflectance from SAIL model for canopies with twigs in them, using measured leaf and twig optical properties and measured background reflectance.

the alder, sitka spruce, and hemlock branches were placed over the Cascade Head litter background. The Oregon white oak was over the Corvallis litter background. The Douglas fir branches were over the Scio litter background. The Metolius soil background was used with the ponderosa pine branches, and the Juniper site soil background was used with the juniper branches. For the SNF sites, the aspen litter was used with the aspen branches, and the jack pine and black spruce were both over sphagnum moss.

Figure 12 displays the modeled canopy red and near infrared reflectances. The value of the background reflectance was important in determining the canopy reflectance for canopies with low values of LAI. Most of the species displayed similar trajectories through red-near infrared reflectance space as leaf area increased. A general decrease in red reflectance and an increase in near infrared reflectance were seen, with the decrease in red reflectance saturating before the near infrared reflectance increase did. Juniper, black spruce, and jack pine were notable, not only for having background reflectances that were very different from the others, but also for having trajectories with increasing LAI that were also quite different. For juniper and jack pine, there was a steady decrease in both red and near infrared reflec-

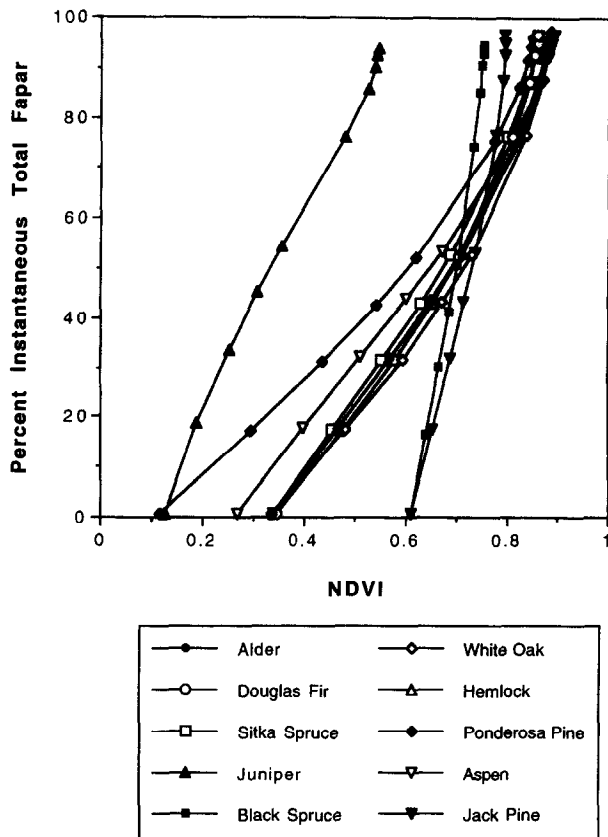


Figure 13. Instantaneous total  $f_{APAR}$  versus NDVI from SAIL model, using measured leaf and twig optical properties and measured background reflectance.

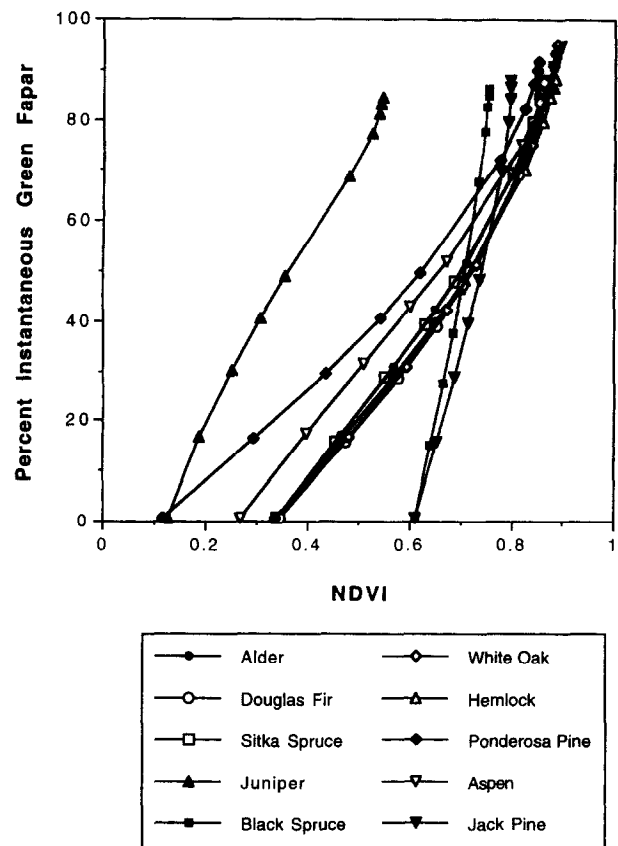


Figure 14. Instantaneous green  $f_{APAR}$  versus NDVI from SAIL model, using measured leaf and twig optical properties and measured background reflectance.

tance with increasing LAI. In black spruce, red reflectance decreased continuously, whereas the near infrared reflectance decreased and then increased with increasing LAI.

As before,  $f_{APAR}$  and NDVI were calculated from SAIL. These results are plotted in Figure 13 for total  $f_{APAR}$  and in Figure 14 for  $f_{APAR}$  absorbed by green leaves only. The use of green  $f_{APAR}$  altered the curves slightly, but the general relations remained the same. All of the relations between  $f_{APAR}$  and NDVI were curved but only slightly. Fitting any of these SAIL model-based relations with a straight line would result in errors of less than 10% in the estimation of  $f_{APAR}$ .

As in the reflectance plot, most of the canopies behaved in a similar manner, except for juniper, black spruce, and jack pine. For the rest of the species, the largest differences in the curves were at low values of  $f_{APAR}$  due to reflectance variations in the background. With the exception of the sites with sphagnum backgrounds, the error in  $f_{APAR}$  estimates for a given value of NDVI was no more than 20% at low values of  $f_{APAR}$ . There were also errors in estimating  $f_{APAR}$  at higher values, because of the curvature in the relations taking an upward turn; these errors also were approximately 20%  $f_{APAR}$ . Adding juniper, black spruce, and jack pine into the mix dramatically increased errors in determining  $f_{APAR}$

from NDVI at both ends of the curves. Although juniper and ponderosa pine had similar background soil NDVI values, the differences in the branch-level optical properties caused the NDVI- $f_{APAR}$  relations to diverge. The differences in the curves caused the error in estimating  $f_{APAR}$  to be as great as 50%  $f_{APAR}$ . For black spruce and jack pine, the trees were not the only part of the scene that was green; the sphagnum moss background had a very high NDVI. For black spruce and jack pine forests, the range of NDVI values was very small: 0.144 NDVI units for black spruce and 0.186 NDVI units for jack pine. The resulting steep slope of the NDVI- $f_{APAR}$  relation for these two species magnified the effects of any errors or noise in the determination of NDVI on the retrieval of  $f_{APAR}$  values. Attempting to determine  $f_{APAR}$  from NDVI over all of the species examined with these backgrounds can result in large errors if the forest type is not known. A closed juniper canopy with a  $f_{APAR}$  of 95% had a NDVI less than that of a treeless sphagnum moss scene.

## CONCLUSION

This study examined the effect of varying leaf, twig, and background optical properties on the determination of  $f_{APAR}$  from NDVI for ten different forest species. Several issues stand out from this analysis. Variations in leaf opti-

cal properties between different species may pose a problem in the determination of biophysical variables. At higher values of LAI, leaf optical properties were the factors that dominated the determination of the canopy reflectance. Green-leaf optical properties, among the species studied, had little effect on  $f_{\text{APAR}}$ . Variations in canopy reflectance due to differences in leaf optical properties were large, but most species had similar NDVI- $f_{\text{APAR}}$  relations. However, juniper, jack pine, and black spruce all had different NDVI- $f_{\text{APAR}}$  relations from those of the rest of the species. These differences can result in significant errors in the estimation of  $f_{\text{APAR}}$ .

Background reflectance is important in open canopies. At low values of LAI, the background reflectance has a significant effect on the canopy reflectance, although little effect on PAR absorption. Variations in background reflectance can result in significant errors in the estimation of  $f_{\text{APAR}}$ .

There is more to vegetation background than soil. Litter reflectance patterns appear to have their own line in red-near infrared space, different from the soils line. In addition, backgrounds may consist of materials with chlorophyll, such as mosses. These background green plants have very different spectral properties from those of soils or litter. The differences in the reflectance patterns of the backgrounds make it difficult to design a general-purpose SVI that can reliably reduce the background variations.

A forest type with vegetation as its background creates a problem of interpretation of the remotely sensed data. An analysis requiring retrieved  $f_{\text{APAR}}$  values for the forest canopy only and that for the canopy and the vegetation background together will produce two very different NDVI- $f_{\text{APAR}}$  relations.

Twigs in the canopy did have an effect on reflectance and  $f_{\text{APAR}}$ , but these effects were secondary to the effects of background and leaf optical properties. The use of green  $f_{\text{APAR}}$  may reduce the variability due to twigs within the same type of canopies but has little effect on the variation between different types of canopies.

This study examined only a few species, and it is difficult to speculate beyond the measurements. To understand the effects of leaf and background optical properties, more species need to be measured. Variations within species also must be examined. Although this study indicated that the amount of twigs in the canopy was a secondary factor, that conclusion is based on few measurements. The relative areas of leaves and twigs in forest canopies need further examination. How much does the leaf to twig area ratio vary with factors such as age? How consistent is the ratio within and between species? Information on canopy optical and structural characteristics needs to be collected for a wide variety of vegetation types if we are to have any confidence in global measurements of biophysical variables.

SAIL models canopies that are horizontally uniform.

Forest canopies consist of collections of tree crowns, resulting in gaps and shadowing not described by the SAIL model. The effects of varying canopy geometry on scene reflectance and  $f_{\text{APAR}}$  will be examined in a later paper.

Many of the problems in determining  $f_{\text{APAR}}$  identified in this study can be mitigated if the vegetation and background types are known beforehand. Classifying an image first allows specific NDVI- $f_{\text{APAR}}$  relations to be used for each class. If these relations are consistent within a given species, then the classification can significantly improve the retrieval of  $f_{\text{APAR}}$  values. This is especially true if there are species such as juniper or black spruce, which have NDVI- $f_{\text{APAR}}$  relations that are very different from most other vegetation types.

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