UNIVERSITY OF HAWAII LIBRARY

SPECTRAL SEPARABILITY AMONG INVASIVE AND NATIVE PLANT SPECIES FOR SATELLITE IMAGE ANALYSIS

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF
THE UNIVERSITY OF HAWAI'I IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

NATURAL RESOURCES AND ENVIRONMENTAL MANAGEMENT

AUGUST 2006

By
Tomoko Suzuki

Thesis Committee:

Tomoaki Miura, Chairperson
James B. Friday
Barbara A. Gibson

We certify that we have read this thesis and that, in our opinion, it is satisfactory in scope and quality as a thesis for the degree of Master of Science in Natural Resources and Environmental Management.

THESIS COMMITTEE

Chairperson

Acknowledgment

This master thesis project involved many people to be completed. First, I would like to acknowledge my thesis committee, Tomoaki Miura, James B. Friday and Barbara A. Gibson, for their advise and support to proceed this project. Without their dedication and assistance, this project would not be finished. I would also thank Jonathan Deenik and Ali Fares for helpful insights as principle investigators of the Mākaha project and Tamara Ticktin, Travis Idol, Lawren Sack, Curt Daehler, Camille Barr for helpful comments on the project based on their expertise. I would like to also acknowledge Michele Harman, Donald A. Mair, Kayo Fujiwara, Arlene J. Sison, Christine Chaplin, Lindsay Manuel, Aurora Kagawa, Joshua Scherette, Shawn Steiman, Rodolfo Martinez, Dean Meason for field and lab assistance. Without their help, it would be impossible to complete the project. This project is a part of Mākaha project by *Mohala I ka Wai* and Honolulu Board of Water Supply. I would like to acknowledge them for giving me a opportunity to work on the project, and Army Corp of Engineering for the corporation in the field. This project was competed under support by T-STAR grant. Lastly, I would like to thank my family and friends for their emotional supports.

Abstract

Comprehending the spatial and temporal dynamics of the alien species infestation is critical to manage invasive plants in Hawai'i. Although recent advances in technologies have made a variety of remotely sensed images providing spatial and temporal information of invasive species available to resource managers, little spectral information are available for plant species on tropical island settings. In this study, we evaluated the capabilities of four major satellite sensors to distinguish nonnative species from native species of Hawai'i at leaf and canopy scales with the ultimate goal of establishing the baseline information for image analysis. The sensors were IKONOS, Quickbird, Landsat-7, Enhanced Thematic Mapper Plus and Advanced Spaceborne Thermal Emission and Reflection Radiometer. The spectral properties of nonnative species: *Psidium cattleianum* (strawberry guava), *Schinus terebinthifolius* (Christmas berry) and, *Coffea arbacia* (coffee) and native species: *Acacia koa* (koa), *Diospyros sandwicensis* (lama) and *Metrosideros polymorpha* ('ōhia) were directly measured at the leaf scale, whereas the canopy spectral properties of the species were estimated using a radiative transfer model constrained with sampled biophysical and chemical components of the species. Statistical analyses determined the ability of these sensors to discriminate among different species. In particular, the sensors with the short wavelength bands resulted in the high discriminability. The relative capability of the spectral bands in determining species separability were different at the leaf and the canopy scales indicating the change in the primary biophysical characteristics affecting the separability from the leaf to the canopy scales. These results suggest the effectiveness of remote sensing techniques for invasive species management in tropical islands.

Table of Contents

List of Tables

List of Figures

CHAPTER 1 INTRODUCTION

1.1 Background

1.1.1 Invasive Plant Species Issues in Hawai'i

Plant invasion is one of the most significant threat to various ecosystems all over the world. Oceanic islands are considered particularly susceptible to such invasion for several reasons: less exposure to different types of disturbances, a small number of species, and taxonomic disharmony and reduced aggressiveness of native biota due to less genetic variety (Loope 1992). In the U.S., the invasions by alien plant species are especially severe in Hawai'i. Nearly 100% of Hawai'i's endangered bird and plant species are threatened by introduced species (Wilcolve *et al.* 1998). Staples and Herbst (2005) listed approximately 9,900 introduced cultivated plant species in Hawai'i, among which 1240 species are listed as naturalized in Hawaiian islands (Wagner *et al.* 2005). Approximately 90 plant species have become invasive and threatened native plant species (Smith 1985). Various grasses, banana poka (*Pssiflora mollissima*), strawberry guava (*Psidium cattleianum*), fire tree (*Morella faya*), kahili ginger (*Hedychium gardenerianum*), Australian tree fern (*Sphaeropteris cooperi*) and clidemia (*Clidemia hitra*) are among the most destructive invading plants (Loope 1999). Miconia (*Miconia calvescens*) which is known to suppress the growth of native plant species by creating deep shadows (Meyer and Florence 1996), was introduced as a horticultural plants in Hawai'i in 1961 (Medeiros *et al.* 1997) and spread through the wet forests of all major islands.

1.1.2 Remote Sensing and Invasive Species Management

One of the important components in plant invasion management is comprehending the spatial and temporal dynamics of the spread of invading population (Hobbs and Humphries 1994). Even though the exigent needs for invasive species management is to prevent introductions of new species and to eradicate those species upon entry, assessments over time and space are essential in detecting, mapping and monitoring spatial distribution, abundance, and population composition of invasive species when the first tasks to prevent entries of new species are unsuccessful (Mack 2005).

Remote sensing has gathered attention as an emerging technology for providing spatial information of invasive species (National Invasive Species Council 2001, U.S. Congress OTA 1993, Schnase *et al.* 2002, Turner *et al.* 2003). The number of publications on applications of remote sensing and geographical information systems to mapping invasive species has been increasing over the years (Joshi *et al.* 2004) as various remote-sensed imagery has become available for civilian uses with the recent advance of computer technologies. Schott (1997) described some prominent advantages of remote sensing. Images acquired by airborne or satellite based remote sensing systems provide information of large scale patterns, trends and interactions. It also provides temporal information by repeatedly acquiring data over the same areas. These attributes would be beneficial to assessments of invasive species infestations (Joshi *et al.* 2004).

1.1.3 Remote Sensing Applications

Remote sensing is a science of acquiring information about the earth's surface without being in contact with it. Airborne or satellite sensors "sense" portions of reflected or emitted electromagnetic (EM) radiation (e.g. visible, near-infrared) of materials in image format. Depending on its chemical compositions and structures, every material reflects or emits EM radiation in different magnitudes with respect to wavelength. These "spectral signatures" are used to differentiate or even to identify surface objects either qualitatively or quantitatively. Land use and land cover maps are, for example, created based on differentiating spectral signatures.

When vegetation is of interest, it is necessary to recognize that many factors influence spectral signatures/properties (reflectance, transmittance, and absorptance). Photons not reflected at the leaf surface then travel into the leaf interior and interact with the chemical and biophysical properties of the leaves, therefore the spectral properties of leaves are controlled by these internal properties of leaves (Asner 1998, Clark *et al.* 2005). Pigments within chloroplasts such as chlorophyll absorb the visible portion of the EM radiation, giving low levels of reflection over the region (Gates *et al.* 1965,Woolley 1971, Baranoski and Rokne 2004). On the other hand, plants hardly absorb any radiation of the near-infrared (NIR) region resulting in high reflectance of the region. The high NIR reflectance is caused by photon scattering in leaf internal cell walls such as spongy mesophyll (Gates *et al.* 1965, Woolley 1971, Baranoski and Rokne 2004). The spectral properties of the far-infrared portion are controlled by water contents in leaves. As water is lost from leaves, the reflectance increases (Woolley 1971, Baranoski and Rokne 2004). Because these chemical and biophysical factors affecting the spectral properties of leaves vary between species, and within species depending on maturity, surface characteristics and thickness of leaves, face/back of leaves and sun/shade leaves (Woolley 1971, Roberts *et al.* 1998), the spectral properties of leaves also vary correspondingly.

At the canopy level, canopy structures such as the amount of leaves and stems (i.e., leaf and stem area index), their orientation (i.e., leaf and stem angle distribution), and background reflectance (soil/litter) largely affect spectral signatures of plants (Asner 1998, Clark *et al.* 2005). The variability in leaf area index and leaf angles is the dominant factor controlling canopy reflectance (Asner 1998). The canopy structures are often largely different between species and within species. By differentiating these spectral properties among the species, vegetation classification at species level can be achieved.

Recent advances in technologies have made various remote sensing data available to resource managers of diverse land use systems. Aerial photography methods have long been utilized for vegetation surveys and weed detection in agricultural lands, rangelands and forests. For example, Hessburg *et al.* (2000) detected the change in the vetgetation composition in Columbia River basin and portions of the Klamath and Great Basins in Oregon using historical aerial photography.

Numbers of satellite-borne multispectral broadband sensors which collect data over a variety of different wavelength ranges (CCRS 2005) are available for detecting invasive species infestations. Dymond and Shepherd (2004) used the Landsat-7 Enhanced Thematic Mapper Plus (ETM+) data and successfully produced a land cover map of the Wellington region in New Zealand with the accuracy of 95%. They were also successful in determining the composition of the indigenous forest. The combination of the Landsat ETM+ image with environmental and topographical data predicted the occurrence of several non indigenous species (Rew *et al.* 2005).

Recently commercial sources of remote sensing data have become available for complementing other multispecral sensors by their high spatial resolutions: GeoEye IKONOS with the spatial resolution of 1m for panchromatic and 4m for mulispectral (blue, green, red and near-infrared) bands and Digital Globe Quickbird with the spatial resolution of 0.7m for panchromatic and 2.8 for multispectral bands.

Airbrone or space-borne hyperspectral sensors, which collect the spectral signatures of the electromagnetic spectrum in narrow and continuous increments (Lass *et al.* 2005), have been proven to be highly effective to detect invasive plants at species level. The colonies of Brazillian pepper (*Schinus terebinthifolius*) in Everglades National Park in Florida were classified accurately with a hyperspectral sensor although the result suggested that it will not be able to use the data to find scattered individual trees (Lass and Prather 2004). Lass *et al.* (2005) detected *Centaurea maculosa* and *Gypsophilapanifulata* in Swan Valley, Idaho with a hyperspectral sensor. Clark *et al.* (2004) showed the high discriminabilities among tropical rain forest trees at the crown scale using 30 optimally-selected bands with the overall accuracy of 92%. The hyperspectral narrowband data also provided the high accuracy of the crown scale classification relative to the accuracies achieved with simulated multispectral broadband data.

In Hawai'i, these remote sensing data are beginning to be explored for the invasive species management. Under Operation Miconia of Big Island Invasive Species Committee (2003), the populations of *Miconia calvescens* were located on the Big Island Hawai'i by aerial surveys. The Hawai'i Gap Project (2005) utilizes Landsat 7 imagery and GIS processing for 8 main Hawaiian islands, to acquire land cover information and spatial distribution data for a number of key species including both native and nonnative species. The infestation of *Morella faya* and *Hedychium gardnerianum* in the Big Island was detected with the combination of hyperspectral data and photon transport modeling (Asner and Vitousek 2005).

1.1.4 Issues

Although many successful cases of invasive species detection have been reported in recent years, some considerations are still to be made when the techniques are applied in Hawai'i. First of all, few studies have addressed the effectiveness of remote sensing methods in invasive species management in tropical islands settings such as the Hawaiian Islands. Secondly, the available sensor systems for Hawai'i are scarce, even though hyperspectral data are proven to be effective to detect invasive plants. Such data of tropical islands are still difficult to financially acquire for many resource managers. According to Lass *et al.* (2005), the cost for hyperspectral data from a commercial company varies between $60,000 and $100,000 for a 20 by 40 km area with 2 to 3m spatial resolutions. The data readily accessible are taken by the multispectral broadband sensors which record EM radiation at several discrete wavelength. The capabilities of these multispectral broadband sensors to discriminate among tropical nonnative and native plants are not defined. Thirdly some features of the Hawaiian Islands could cause complications when the remote sensing techniques are applied. Since it is known that topography can modulate remotely sensed signals (Myneni *et al.* 1995), highly rugged terrains typical in Hawaiian Island ecosystems may create shadows in images masking vital information of the area. Heterogeneous native forests could result in mixture of spectral signatures and therefore unable to separate species out (Foody 2002, Powell *et al.*

2004). Finally there is little spectral information of both native and invasive tropical plant species available (Sánchez-Azofeifa *et al.* 2003) therefore the separabilities among the native and invasive plants in Hawai'i are not definitive. The effectiveness of remote sensing techniques to the management of biology invasion in Hawai'i needs to be examined further.

1.2 Objectives

This study was originated by a collaborative project between *Mohala I ka wai*, a community group in Waianae, Oahu and Honolulu Board of Water Supply (HBWS). They are concerned with the decline of Mākaha stream, which runs through the center of the Mākaha valley, Oahu and question the influence of water pumping by HBWS started in 1960s and of the infestation of invasive plant species in the valley. One of the objectives of the project is to create a vegetation map of the valley using remote sensing techniques to provide spatial extent and biogeophysical condition of invasive and native vegetation communities in the valley. This study is thus aimed particularly at developing the effective remote sensing technique in support of management of alien plant invasions in Mākaha valley, and further, in tropical islands like Hawaiian Islands. The specific objectives of the study are:

Objective 1) To determine spectral separability among native and nonnative plant species of the Hawaiian Islands at leaf to canopy scales for satellite sensors available to resource managers.

Objective 2) To evaluate and compare the performance of the available sensors to discriminate among the species and to determine the sensor or band configuration that would provide the best potential discrimination capability.

Objective 3) To identify key biophysical factors of plants contributing to separation of native and nonnative species in remotely sensed signals.

1.3 Hypothesis

Hypothesis 1) Native and nonnative plant species of Hawai'i are spectrally separable at leaf level as well as at canopy level.

Hypothesis 2) Sensors with SWIR bands are more capable of discriminating among species than ones without SWIR bands.

Hypothesis 3) The influence of certain physical characteristics of canopies (Leaf Area Index, Leaf Angle Distribution, Non Photosynthetic Active Vegetation Area Index and Non Photosynthetic Active Vegetation Angle Distribution) on canopy reflectance is larger than the one of chemical properties of leaves therefore contributing more on the separation or non separation among the species.

CHAPTER 2 MATERIALS AND METHODS

2.1 Overview

The separabilities of reflectance among native and invasive plant species in Hawai'i was analyzed at two scales: leaf and canopy levels. Leaf reflectance were measured with a spectrometer. Due to the difficulty to acquire *in situ* top of canopy reflectance, canopy reflectance were modeled with a canopy radiative transfer model. Both types of reflectance were spectrally convolved to simulate the band responses of four common multispectral satellite sensors: Landsat-7 Enhanced Thematic Mapper Plus (ETM+), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), IKONOS and QuickBird. Two types of statistical analysis were conducted to examine the abilities of individual bands as well as the sensors to separate the species.

2.2 Study Site

The study area was located in Mākaha Valley on the leeward side of the Island of O'ahu, Hawai'i. The area is dry and brush fire is often problematic during dry summer season. According to the Western Regional Climate Center, the annual average temperature of the lower part of the valley from 1997 to 2004 was 24 Celsius degree. The mean annual precipitation is between 1000 mm to 2000 mm (Giambelluca *et al.* 1986). Mākaha stream in the valley provides water resources and recreational opportunities to the local communities downstream. The back portion of the valley is owned by Honolulu Board of Water Supply (HBWS) and designated as a conservation area.

The area has been invaded by various nonnative species including Java plum (*Syzygium cumini*), Australian red cedar (*Toona ciliata*), Christmas berry (*Schinus terebinthifolius*) and strawberry guava (*Psidium cattleianum*). These species dominate the most of the area in the valley. The invasion is especially severe in the lower part of the valley. Native plant species are found only in the higher elevation areas as small, scattered patches. Various conservation works have being conducted by the HBWS, Army Corp of Engineering, and University of Hawai'i to protect the ecosystem and the native species in the area.

Three species each from native and nonnative plants in the valley were selected for this study. These six tree or shrub species are relatively dominant in the Mākaha valley, thus, would contribute significantly to remotely sensed signals. The native species were 'ōhia (*Metrosideros polymorpha*), lama (*Diospyros sandwicensis*), and koa (*Acacia koa*). The nonnative invasive species were Christmas berry (*Schinus terebinthifolius*), strawberry guava (*Psidium cattleianum*) and coffee (*Coffea arabica*). 'Ōhia is endemic to Hawai'i and dominant in shrublands, and mesic to wet forests (Wagner *et al.* 1999). Lama is also endemic to Hawai'i. It is scattered to dominant in some types of dry to mesic forest, also extending to wet forest (Wagner *et al.* 1999). Koa, endemic to Hawai'i, is often dominant in dry to wet forest. Christmas berry is native of Brazil, Argentina and Paraguay (Ewel *et al.* 1982). It has aggressively colonized various types of lands in Florida particularly reported in Everglades National Park (LaRosa *et al.* 1992). It was first recorded in 1909 in Hawai'i and introduced as an ornamental plant (Wester 1992). Strawberry guava is native to the central and south America regions, and one of the most serious weeds in Hawai'i often forming dense monotypic stands in disturbed mesic forest and wet forest (Wagner *et al.* 1999). It was first reported in 1908 in Hawai'i and introduced as a crop plant (Wester 1992). Coffee is possibly native of Ethiopia and it is widely cultivated and well naturalized in Hawai'i primarily in mesic to wet, disturbed sites, usually valleys or along streambeds (Wagner *et al.* 1999). It was introduced to Hawai'i as a crop plant in 1823 (Wester 1992).

2.3 Field and Lab Measurement

Six 32 m-by-32 m plots were drawn in the upper portion of the valley (Figure 1). The plots on the steep slope were adjusted for the slope by lengthening slope distance to acquire the 32m horizontal distance. Each plot contains one dominant species of the six species. For koa and 'ōhia , two combined plots for these two species with some other native plant species were set due to the scarcity of sufficient coverage of these species in the valley. All the plots were placed on the northern facing slope of the valley to avoid the variability of the solar radiation effects due to the aspects of the valley. The altitudes of the plots are approximately 300 to 800 m above the sea level. The following parameters influencing canopy and leaf reflectance were sampled and measured from the plots for each species.

2.3.1 Plant Area Index and Fractions of Leaf and Wood Area

Plant Area Index (PAI), which is defined as one half the total surface area of leaves and supporting woody materials per unit ground surface area (Chen 1996), was measured for each species using a LAI-2000 plant canopy analyzer (LI-COR, Nebraska, USA). The instrument determines the canopy light interception (e.g. canopy gap fraction) by the light measurements made above canopy and below canopy at 5 angles simultaneously. The gap fraction was then inverted with a radiative transfer model to estimate the plant area index (Miller 1967, LI-COR Inc 1992, Chen and Cihlar 1995). The calculation is based on the assumption of the random foliage distribution (LI-COR Inc 1992, Chen and Cihlar 1995). The measurements were taken at the centers of the grids created by dividing the plots into 4m by 4m grids (64 grids per plot). 5 samples per grid were measured: therefore a total of 320 samples per plot was taken. To minimize the contribution of scattered radiation, which causes underestimation of PAI, the 45° view caps were used to mask the portion of the sky containing the sun and the measurements were taken under diffuse sky condition.

Many optical instruments including LAI-2000 uses canopy gap fraction to indirectly estimate Leaf Area Index (LAI). The gap fraction measured by these instruments, however, includes the light interception by woody components therefore PAI instead of LAI is estimated from the fraction (Chen 1996 and Kucharik *et al.* 1998). To separate the PAI measured by LAI-2000 into leaf and wood portions, the photographs of canopy were taken at the centers of the grids. Then, fractions of leaf and woody parts were estimated. Systematically selected 180 points within each photograph were classified into leaf or wood to estimate the fractions. These fractions were multiplied with the PAI values to estimate Leaf Area Index (LAI) and Non Photosynthetic Vegetation Area Index (NPVAI) of each plot.

2.3.2 Leaf Angle Distribution and Non Photosynthetic Vegetation Angle Distribution

Leaf Angle Distribution (LAD) and Non Photosynthetic Vegetation Angle Distribution (NPVAD) were estimated from the direct measurements of the leaf and stem angles of each species. The zenith angles ranging from 0° (horizontal) to 90° (vertical) were measured with an inclinometer. A total of 500 angles of the leaves for each species were sampled. For the stem angles, the measurements were taken at a midpoint between a start of a stem and an end of the stem or a beginning of new stem/branch. More than 300 angles of stems were directly measured for each species.

2.3.3 Leaf and Bark Spectral Properties

Fifty fresh leaves were harvested in the field and the spectral properties for a full range wavelength (400-2500 nm) were measured using a spectroradiometer (Field Spec Pro FR, Analytical Spectral Devices Inc., Colorado USA) equipped with an external integrating sphere (LI-1800, LI-COR, Nebraska, USA) within 24 hours after harvesting.. The ASD spectroradiometer records the EM energy reflected or transmitted by objects with 1 nm intervals. Daughtry's operational procedures for measuring reflectance and transmittance of plant tissue samples (Daughtry *et al.* 1989) was modified to measure both adaxial and abaxial sides of the leaves . The measured adaxial and abaxial spectra were then averaged to produce one reflectance and transmittance spectrum each for one leaf. Fifteen bark samples for each species were harvested in the field and also measured with the ASD spectroradiometer attached with the integrating sphere but only the reflectance of the adaxial side were measured under the assumption that no photon is transmitted through stems.

2.3.4 Soil and Litter Spectral Properties

Soil and litter samples were collected at 3 randomly located grids within each plot for background reflectance measurement. The soils from S. guava and C. berry plots are classified as clayey, kaolinitic, isohyperthermic rhodic eutrustox Halemano series, which is Oxisols that have ustic moisture regime (USDA-NRCS). The soils of the other plots are classified as Tropohumults-Dystrandepts association, which are soils on the rocky and steep slope area (USDA-NRCS). Although the classifications are outdated for the Tropohumults-Dystrandepts association, the official soil survey has not been updated yet. According to the personal communication with Christopher Smith, a USDA-NRCS soil scientist in Hawai'i, Tropohumults would become Hapludults or Haplustults and Dystrandepts would become Hapludands and Haplustands with the breakdown between udic and ustic soil moisture regimes (udic>1500 mm, and ustic <1500 mm annual rainfall).

The reflectance of the collected soils and litters were measured separately with the ASD spectroradiometer. The measurements were conducted within two hours of Hawai'i local noon (12:30 pm). A white calibration panel (Spectralon, Labsphere, New Hampshire, USA) was used to convert from radiance values to reflectance. The fiber optic of the spectroradiometer was held constant at 25 cm above the soils and the litter with the linear field of view of 5 cm. To capture variability of the back ground condition, the reflectance were measured with the wet and dry condition. First the soils and litters, which were air-dried after the collection, were measured, then they were wetted with water before the measurement and the reflectance were measured with the moderately wet condition (not saturated). Due to weather constraints, however, only reflectance of S.guava and C.berry plots (Halemano series) was measured. Therefore, a total of 6 soil (wet and dry) and litter (wet and dry) reflectance were collected for S. guava and C. berry. The measured reflectance were used for the background reflectance for the other species.

In the field, the fractional coverage of the ground (soil versus litter) for each plot was then measured with a point intersection method. Five 10 m transects were randomly placed within each plot and the ground cover (either soil or litter) was identified every 10 cm. The measured reflectance of soil and litter were weight averaged with the estimated fractions and the reflectance of the ground surface mixing litter and soil were estimated for each plot.

2.4 Radiative Transfer Modeling

Canopy-level or top-of-canopy (TOC) reflectance of each of the species were simulated using a Scattering by Arbitrarily Incline Leaves (SAIL) canopy reflectance model (Verhoef, 1984). The model estimates the TOC reflectance using the values of geometry (sun and view zenith and azimuth angles) structure (LAI, NPVAI, LAD and NPVAD), and tissue spectral properties (leaf and bark reflectance and transmittance) and soil reflectance (Asner 1998),

$$\rho_c(\lambda) = f(T, S, G, \rho_{sl}(\lambda)) \quad (1)$$

where $\rho_c(\lambda)$: Canopy level reflectance, T: tissues (leaf and bark reflectance (ρ) and transmittance (τ)), S: structure (LAI, NPVAI, LAD, NPVAD), G: geometry (Sun and view zenith and azimuth angles) and $\rho_{sl}(\lambda)$: background reflectance (Soil and Litter).

To determine the potential range of variability in canopy reflectance, the parameters were perturbed within possible ranges (Table 1) to produce 10,000 TOC spectra for each species. For the tissue spectral properties and soil reflectance, one spectrum each was chosen from the measured spectra. Since transmittance is the residue of photons not reflected or absorbed, reflectance and transmittance of a leaf are correlated.

Therefore, corresponding measured reflectance and transmittance of a leaf were paired. PAI value was selected from the range between the minimum and maximum values for each species. The fractions of leaf and wood area, which were paired, were randomly selected from the ranges between the minimum and maximum values, and multiplied to a fore-chosen PAI value to derive LAI and NPVAI. LAD and NPVAD were modeled as an ellipsoidal angle distribution with mean leaf and NPV angles (Campbell 1990). The examples of the modeled LAD and NPVAD are shown in Figure 2. Mean angles of leaf and NPV were perturbed within ± 10 % of the means of the measured angles. In this study, the hypothetical geometrical values were held constant: the solar zenith and azimuth angles as 21° and 0°, respectively, and the view zenith and azimuth angles as both 0°.

2.5 Spectral Separability Analysis

Spectral analyses were conducted at two different scales, i.e., at leaf and canopy levels. The measured/modeled hyperspectral reflectance and transmittance were spectrally convolved to the spectral response curves of the following multispectral broadband sensors: Landsat-7 ETM+, ASTER, IKONOS, and QuickBird (Table 2). The band locations and widths are displayed in Figure 3. Landsat-7 ETM+ is a popular satellite-borne sensor launched by National Aeronautics and Space Administration (NASA) in 1999. The sensor provides 30 m multispectral images in 4 bands in visible/near infrared (VNIR) wavelength regions and 2 bands in short wave infrared region (SWIR) wavelength regions. ASTER is a satellite-borne sensor launched in 1999 and a collaborative effort between NASA and Japan's Ministry of Economy Trade and Industry (METI) with the scientific and industry organizations in both countries. The sensor has 3 bands in VNIR wavelength regions with 15 m spatial resolution and 6 bands in SWIR regions with 30 m spatial resolution. IKONOS is the world's first commercial high –resolution imaging satellite launched in 1999 and operated by GeoEye. It provides 1m panchromatic and 4m multispectral images in 4 bands in VNIR wavelength regions. Quickbird is also a commercial satellite with high spatial resolution launched in 2001 by Digital Globe. It provides 72 cm panchromatic and 2.88 m multispectral images in 4 bands in VNIR wavelength regions.

Two statistical methods were then applied to the convolved reflectance and transmittance in order to assess the spectral similarities and dissimilarities among the species. The maximum likelihood classification algorithm was used to examine the capability of each sensor to discriminate the spectral signatures of the species. The algorithm calculates the likelihood of an unknown spectrum belonging to each of the classes which were predefined by training data sets and assigns the spectrum to that class where the likelihood is maximized.

$$f \in \omega_i \text{ if } p(\omega_i|f) > p(\omega_j|f) \text{ for all } j \neq i, \quad (3)$$

i.e., the spectrum f belongs to class ω_i if $p(\omega_i|f)$ is the largest (Richards and Jia, 1999). $p(\omega_i|f)$ is a posteriori probabilities that the spectrum belong to each of the training classes ω_i, given that the spectra have the feature vector f (Schowengerdt 1997). For the leaf level analysis, all 50 spectra of each species were used as training data to predefine 6 vegetation classes and each spectra was assigned to that class where the likelihood is maximized. For the canopy level analysis, due to the large number of samples, randomly selected 1,000 spectra from 10,000 spectra of each species were used as training data to predefine the classes. All the estimated 60,000 spectra were then assigned to that class where the likelihood is maximized.

The overall accuracies were calculated by summing the number of spectra classified correctly and dividing by the total number of spectra. The producer accuracy is a measure indicating how many of the spectra assigned to a class have been correctly labeled. The user accuracy is a measure indicating how many of the total number of spectra for a species have been correctly classified. Errors of commission represent spectra that belong to another class that are labeled as belonging to the class of interest. Errors of omission represent spectra that belong to the class of interest but the classifier has failed to classify them into the proper class.

Secondly, *t*-test was used to examine the separabilities among the species and between the native and nonnative species at different wavelength regions or the bands The analysis was expected to generally explain which structural and chemical components influence most on the separabilities among the species. A mean reflectance/transmittance value of one species at a band were compared to mean values of the other species at the same band. The desired significant level 0.01 was divided by the number of comparisons for one mean value ($n = 5$) to obtain individual critical points for the multiple comparisons (Bonferroni correction, Miller 1981). When $P < 0.002$, two species were considered to have significantly different means of spectra at a particular band, therefore they are separable. The results were then summarized into three categories: A) species separable from all the other species ($P < 0.002$ for all species), B) species separable from another group (e.g. native or nonnative), and C) species not separable from another group ($P \geq 0.002$ for one or more species from another group).

To further identify the relationship of the leaf and canopy reflectance with the structure and chemical contents of leaf and canopy, the Normalized Difference Vegetation Index (NDVI) (e.g., Tucker 1979) was also examined by *t*-test:

$$NDVI = \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red}} \tag{2}$$

where ρ_{NIR} is the reflectance of near infrared (NIR) bands and ρ_{red} is reflectance of the red bands. The relationship between NDVI and LAI has been extensively studied and the positive logarithmic correlation between them is usually observed (Gamon *et al.* 1995 and Roberts *et al.* 2004). Gamon *et al.* (1995) also described the positive logarithmic relationship between NDVI and the chemical components within canopy (e.g. Chlorophyll and Nitrogen contents). Therefore the separabilities of the species with NDVI were expected to explain the relationship between spectral properties of the species and the structure and chemical components of leaf and canopy. Also, for the sensors without the SWIR bands such as IKONOS and QuickBird, the difference between red and NIR bands is one of the keys to differentiate the species.

CHAPTER 3 RESULTS

3.1 Canopy Structural Data

The mean and first degree of standard deviation of PAI, leaf angles and NPV angles for each species are summarized in Table 3. The frequency distributions of these data are displayed in Figure 4, Figure 5 and Figure 6, respectively. PAI was concentrated around the value of 4 for all the species (Figure 4). The native species, however, had smaller PAI values (PAI = ~1 to 2) than the nonnative species.

The distribution of leaf angles for each species is shown in Figure 5. All the nonnative species had similar LAD peaking around 20 degrees suggesting the leaves of the nonnative species were horizontally faced up. On the other hand, the native species had different LAD among another, and from the nonnative species. The peak angles of these species were higher than the nonnative species suggesting that they had more vertically oriented leaves. The mean leaf angles also showed the differences between the native and nonnative species (Table 3).

The distribution of NPV angles for each species is shown in Figure 6. Due to the differences of the sample sizes among the species, the data were normalized with the number of samples taken for each species. Generally, the peaks were observed around 20 to 30 degrees which were mainly branches close to leaves, and 80 to 90 degrees which were mainly trunks. The mean angles did not show particular differences between the native and the nonnative species (Table 3).

3.2 Hyperspectral Data

3.2.1 Bark and Background Reflectance

The mean hyperspectral bark reflectance for each species is shown in Figure 7. The variability of the spectra within the species were relatively large and constant throughout the wavelength for all the species except for the S. guava (Figure 8).

The mean hyperspectral soil/litter reflectance for each species is shown in Figure 9. The water vapor absorption feature resulted in the high noise of the SWIR wavelength (1700 – 1900nm). The spectral signatures were basically the same across the plots: they differed only in the magnitude due to different levels of litter cover. The variability of the spectra within the species increased as moving toward longer wavelengths (Figure 10).

3.2.2 Leaf Reflectance

The mean leaf reflectance of each species are shown in Figure 11. The variability of the spectra within the species were considerably small for all of the species (Figure 12). Although some subtle differences among the species were visually observed, the overall patterns of the optical properties were similar among invasive and native species as most of plant tissues consist of similar chemical components. In the visible wavelength region (400 – 700 nm), the reflectance was low as a result of the light absorption by pigments within the leaves. Lama had higher reflectance than the others over the visible region suggesting low light absorption by the pigments, while koa had the lowest reflectance with high light absorption. In the near-infrared (NIR) region (700 – 900 nm), leaves hardly absorb any radiation due to the scattering by leaf surface and interior structure. S. guava gave off the highest NIR reflectance, while koa and ‘ōhia had the lowest reflectance. The spectral properties of the shortwave-infrared (SWIR) portion (SWIR 1:

1550 – 1750 nm and SWIR 2: 2150 – 2300 nm) are controlled by water contents of leaves. Coffee had the highest reflectance likely due to the lower water contents in the leaves relative to the others. Koa and ‘ōhia again, had the lowest reflectance over the SWIR regions.

3.2.3 Leaf Transmittance

The mean hyperspectral leaf transmittance for each species is shown in Figure 13. Transmittance is the remnant of the light after reflected by the surface and the interior structure of leaves and absorbed by the interior constituents of leaves. The spectral patterns of the transmittance were more similar among the species than those of the reflectance in that they differed only in the magnitude. Similar to the leaf reflectance, the variability of the spectra within the species were small for all the species (Figure 14). Only ‘ōhia had a slightly different spectral signature i.e., its contrast between NIR and VIS/SWIR was higher than that of the other species. A high level of coffee transmittance and a low level of S. guava transmittance over the SWIR wavelength were observed. Although the SWIR reflectance of lama, S. guava and C. berry were similar, the transmittance of these species at the SWIR wavelength were different suggesting the differences in the light absorption by water among these three species.

3.2.4 Canopy Reflectance

The average simulated reflectance of canopy for each species showed more variability among the species than the leaf reflectance spectra (Figure 15). The shapes of the spectra remained similar to the leaf reflectance. The reflectance due to the pigments concentration over the visible wavelength decreased for all the species compared to the leaf reflectance. This decrease was likely due to an increase in light absorption by multiple leaf layers. On the other hand, the variability among the species over the NIR region was especially prominent, although the variability within the species over the region was significantly larger than that of the leaf reflectance as the standard deviations increased (Figure 16). The lower variability of S. guava spectra for all wavelength regions relative to the other species were observed. All nonnative species consistently showed higher NIR reflectance than the native species. Similar to the leaf reflectance, coffee had high reflectance over the SWIR regions. On the other hand, S. guava had low reflectance over the SWIR regions. The reflectance values at 1350 – 1430 nm and 1800 – 1970 nm were excluded from the analysis due to the high noise caused by water vapor absorption.

3.3 Multispectral Data

3.3.1 Leaf Reflectance and Transmittance

The mean broadband reflectance and transmittance spectra for each sensor are shown in Figure 17 and Figure 18 respectively. Regardless of the simplifications of the spectra thru the band convolution, the spectra showed the same general spectral patterns, contrasts and signatures observed in the hyperspectral reflectance and transmittance. It should, however, be noted that the spectral features captured by the two four band sensors, IKONOS and QuickBird, were more similar among the species due to the lack of the SWIR bands.

3.3.2 Canopy Reflectance

The multispectral data of the canopy reflectance showed the similar pattern to the hyperspectral data. The loss of the information over the SWIR regions with IKONOS and QuickBird might have made it difficult to achieve discrimination at species level, even though the differences over the NIR regions might separate the nonnative and native at group level. A decrease in the overall reflectance comparing to the leaf reflectance were observed for all the species except for the NIR reflectance of coffee and S. guava. The decrease is likely due to multiple photon scattering caused by the plant architecture. Band 9 of ASTER (2396 nm) was excluded from the analysis due to the high level of noise. The visual analysis of the mulispectral data indicated that spectral discrimination by ASTER and ETM+ would be based on the differences in spectral signatures from the visible to SWIR regions, while one by IKONOS and QuickBird would be based only on the contrasts of spectra between the visible to NIR regions.

3.4 Maximum Likelihood Analysis

3.4.1 Leaf Reflectance

The overall accuracies of the classification were more than 90 % for all of the sensors suggesting high separabilities among the species (Table 4). The accuracies were 99.33 %, 97.00 %, 93.00 % and 90.67 % for ASTER, ETM+, QuickBird and IKONOS, respectively. The patterns of the inter-class confusion among the species were different depending on the sensors. ASTER produced the highest accuracy of all with the misclassification of only two spectra (Table 4 a). Lama and coffee had no inter class misclassification with the other species (no commission or omission error). The result indicated a slight probability of ‘ōhia to be misclassified as koa and S. guava to be classified as C. berry. For this study, native and nonnative species spectra were separated perfectly from each other with ASTER.

ETM+ produced the second highest overall accuracy (Table 4 b). S. guava had no inter class misclassification with any of the species. Koa and 'ōhia were discriminated from all the nonnative species. The spectra of C. berry were mixed with lama and coffee lowering its producer accuracy to 90 % and user accuracy to 93.75 %.

The accuracy of IKONOS was the lowest of all the sensors, and was approximately 10 % lower than ASTER (Table 4 c). The sensor separated S. guava from the others without any misclassification. The commission error of coffee was prominently higher than the other species (20 %) and some 'ōhia and C. berry spectra were wrongly classified as coffee. The omission error of C. berry were higher than the other species with 22 % probability of the misclassification as lama, 'ōhia and coffee. Koa and 'ōhia did not mix with lama likely due to the constantly higher reflectance of lama through the wavelength. Koa and C. berry separated perfectly from each other, even though they both mix with coffee for small probabilities.

Although the overall accuracy of QuickBird were higher than that of IKONOS, no species was classified perfectly without inter class misclassification (Table 4 d). Similar to the result of IKONOS, the commission error of coffee was relatively higher than the other speices, with the misclassification of some koa and C. berry spectra into the class. The omission error of C. berry was also prominent with 20 % probability of the misclassification as lama, 'ōhia and coffee.

C. berry produced the lowest producer accuracy with all the sensors except ASTER, whose overall accuracy is the highest among the sensors. The user accuracy of coffee was the lowest for both IKONOS and QuickBird which do not have SWIR bands. S. guava had both user and producer accuracies high. Koa and ‘ōhia never mixed with lama for all the sensors, although they mixed with either C. berry or coffee which had some misclassification with lama.

3.4.2 Leaf Transmittance

The overall accuracies of the classification for the transmittance were also high, more than 95 % for all the sensors (Table 5). The order of the accuracies were same as the reflectance: ASTER was the highest with 98.33 % and IKONOS was the lowest with 96.67 %. The differences in the accuracies among the sensors were 2 %, which are smaller than the ones of the reflectance (approximately 10 %), suggesting less effect of SWIR bands and highly distinctive spectra of the species over the visible and NIR wavelength.

The patterns of the species interactions were similar among the sensors. All of the sensors successfully separated the species into the native and nonnative groups. With ASTER, S. guava and lama were separated with no inter class confusion (Table 5 a). As observed with the reflectance, koa did not mix with lama for all of the sensors. Coffee and C. berry had both produced low producer and user accuracies for all of the sensors, while the high producer accuracies of lama and the high user accuracies of koa were observed.

3.4.3 Canopy Reflectance

The results of the maximum likelihood classification for the canopy reflectance are summarized in Table 6. The overall accuracies were lower for all of the sensors relative to the accuracies of the leaf level classifications likely due to high variability of spectra within the species. The differences in the accuracies between the sensors with SWIR bands and the ones without SWIR bands were obvious. ASTER and ETM+ produced 95.60 % and 94.96 % accuracies respectively while IKONOS and QuickBird had approximately 15 % lower accuracies than those sensors (79.70 % and 79.30 %, respectively). No species was classified without any inter class confusion with any of the sensors. Not only the overall accuracies, but also the interaction patterns among the species were different depending on whether a sensor has SWIR bands or not. For ASTER and ETM+ (Table 6 a and b), the inter class misclassification was observed between koa and ‘ōhia and between lama and C. berry. C. berry also mixed with all the other species. Coffee and S. guava had higher separabilities from each other and from the other species. S. guava especially produced 100 % producer accuracy with ASTER. The rate of the species interactions were higher for IKONOS and Quickbird as the overall accuracies were significantly lower than ASTER and ETM+ (Table 6 c and d). Koa mixed with ‘ōhia while ‘ōhia and C. berry were misclassified each other. Most of the omission error of lama came from C. berry. Coffee and S. guava were also not separated from C. berry and from each other, while ASTER and ETM+ produced high separability between coffee and S. guava.

S. guava had the highest producer accuracies with all the sensors, while the highest user accuracies were shared by S. guava and coffee. C. berry produced the lowest user accuracies for all of the sensors. For ASTER and ETM+, the lowest producer accuracies were produced by C. berry. The spectra of C. berry, which were not classified correctly, were mostly assigned to lama. ‘Ōhia had the lowest producer accuracy with

IKONOS and QuickBird. The misclassified 'ōhia spectra were mostly assigned to C. berry and koa.

3.5 t-test

3.5.1 Leaf Reflectance

The t – test results for the leaf reflectance are summarized in Table 7. None of the sensors particularly indicated superiority over the others as the common bands cover the similar portions of the wavelength regions, e.g., visible, NIR and SWIR. The performance of the bands to discriminate the species was different with in these wavelength regions. The subtle differences in the results among the sensors were due to the locations, widths of the bands. With visible bands, 3 species were possible to be discriminated from the other species (Table 7 a – c). Lama was separable with all the visible bands. Koa were able to be discriminated with the green and red bands. Coffee was discriminable with the blue bands of IKONOS and QuickBird. The green and red band of IKONOS separated S. guava and C. berry from the others and from each other. The other sensors mixed them each other but separated from the native species.

With the NIR bands, only S. guava was discriminated with its high NIR reflectance (Table 7 d). Koa and 'ōhia reflectance were similar through the NIR and SWIR wavelength (Table 7 d – f), but their lower reflectance relative to the others separated them from the nonnative species. As shown in the hyperspectral and multispectral data, coffee had distinctively high spectra over the SWIR regions, therefore SWIR bands of both ASTER and ETM+ were able to separate it from the others (Table 7 e and f).

Despite the ineffectiveness of NIR bands, the mean differences of NDVI calculated with the red and NIR bands were significant for four species koa, lama,, coffee and C. berry (Table 7 g). Although S. guava had prominently high NIR reflectance spectra, its differences between the red and NIR bands were similar to 'ōhia .

3.5.2 Leaf Transmittance

For the transmittance, more species were separable in general compared to the reflectance (Table 8). A total of four species were discriminable with the visible bands (Table 8 a – c). S. guava was separated from the others with all the visible bands. 'Ōhia was discriminable with the red and green bands. Koa and lama were discriminated with the green bands and the red bands, respectively.

The NIR bands were able to separate koa and C. berry (Table 8 d). The importance of SWIR bands were particularly shown with the transmittance (Table 8 e and f). The bands in SWIR 1 region (1550 nm – 11750 nm) were effective in separating four species: lama, 'ōhia, coffee and S. guava (Table 8 e). The SWIR transmittance were all similar for native species, but they were different from the nonnative species. All the nonnative species were separable individually with the SWIR bands. Since s. guava and C. berry had similar reflectance over the SWIR regions, the separabilities between them with the SWIR transmittance suggest the different light absorption by water of the two species.

3.5.3 Canopy Reflectance

Considerably less separation among the species was observed for all the bands at canopy level compared to the leaf level analysis (Table 9). In the visible wavelength region, only koa and 'ōhia were separable with the green bands of all the sensors. IKONOS discriminated coffee from the others with its blue and green bands. The red bands were not effective in separating the species resulting in the high inter class confusion between the native and nonnative species (Table 9 c).

All of the sensors performed similarly for the NIR bands separating the native and nonnative species and mixing within the groups (Table 9 d) including C. berry which was separated from all the other species with the NIR bands. The differences of reflectance in the NIR bands largely influenced the separabilities of the species using NDVI. Although there was small probability of koa and C. berry to be mixed, the native and nonnative species were highly separable with NDVI for all of the sensors (Table 9 g). The SWIR bands of 2100 – 2350 nm wavelengths (Band 7 of ETM+ and Band 6 of ASTER) were the most effective among all the bands (Table 9 e). Especially with ASTER, 4 species (koa, coffee, S. guava and C. berry) were discriminated and lama and 'ōhia were different from the nonnative species.

CHAPTER 4 DISCUSSION

In this study, the spectral separabilities among 6 native and nonnative plant species of Hawai'i were examined at leaf and canopy scales for four multispectral satellite sensors. These species were separable at the leaf and canopy scales with high accuracies using the Maximum Likelihood algorithm although a decrease in the classification accuracies was observed from the leaf to the canopy level. At the leaf level, all the sensors produced more than 90 % overall accuracies. The differences in the accuracies among the sensors were due to the number of bands and the width and locations of the wavelength to be used. The small variability of the leaf spectra within the species contributed to the high accuracies of the separation. S. guava were classified almost perfectly with all the sensors with the distinctively high NIR reflectance. The others had the small probabilities of the inter-class confusion. Koa and 'ōhia never mixed with lama because of their considerably lower reflectance for all the wavelength regions.

The advantage of the SWIR bands in discriminating species were clearly indicated at the canopy scale. The sensors with the SWIR bands, e.g., ASTER and ETM+, produced approximately 15 % higher classification accuracies than the ones without them, e.g., IKONOS and QuickBird. The importance of the SWIR band were reported in Clark *et al.* (2005) and supported by their hyperspectral classification. Despite of such advantages of the SWIR bands on the separabilities of the species; however, the difference in the accuracies between ASTER and ETM+ at canopy scale were not observed in this study, indicating that ETM+ may have the minimum number of the bands to produce the high accuracy for the discrimination among the species.

Due to the larger variability of the spectra within the species, more inter-class misclassifications were observed at the canopy level where the influence of the physical characteristics of plants (e.g. LAI, NPVAI, LAD and NPVAD) was introduced. S. guava and coffee were separable with ASTER and ETM+ because of their clearly different SWIR reflectance, but they mixed each other with the sensors without the SWIR bands. Koa and ʻōhia had a tendency to mix each other for all the sensors, while ʻōhia mixed with the other species with IKONOS and QuickBird resulting in the low producer accuracies. Lama and C.berry had high probabilities to be misclassified each other, but C. berry also mixed with the other species producing the lowest user accuracy for all the sensors.

Since the spectral properties of vegetation are influenced by different factors at different wavelength, the t – test, which examined the separabilities among the species at different wavelength regions or bands, indirectly explained which factor influenced most on the separabilities. The results revealed that the effective bands to separate the species were different at leaf and canopy scales. At the leaf level, the visible bands were relatively effective in the separation of three species as absorption of light by pigments within leaves is different among the species. The SWIR bands were also important when a species had distinctively different water vapor absorption, such as coffee. The NIR bands were not effective in separating the species at the leaf level suggesting scattering by the surface and internal structure of the leaves were not different among the species.

For the canopy level, less species were separated with all the wavelength regions. Therefore the differences in NIR reflectance between the native and nonnative species were conspicuous. Fewer leaves and stems in the canopy will cause less photon scattering within the canopy, therefore less NIR reflectance. Considerably less PAI of all three native species compared to the nonnative species (Table 3 and Figure 4), likely resulted in the low NIR reflectance. Leaf Angle Distribution, which also affects the photon scattering (Asner 1998) was higher for the native species than the nonnative species (Table 3 and Figure 5), i.e., the nonnative species facing upward considerably more than the native species. The result of NDVI was influenced by such large differences among the species over the NIR region as the native and nonnative were perfectly discriminated.

Even though the results encouragingly showed that these selected native and nonnative species were separable with the multispectral sensors with relatively minimal inter-class confusions, the applicability of the results of this study needs to be carefully considered. The results are unique to the 6 native and nonnative species in Mākaha valley therefore the generalization of the results to other Hawaiian native and nonnative plants may be difficult. Other native and nonnative plants may not have the distinctively different attributes (e.g. PAI and LAD) which largely influenced the separabilities of 6 species selected for the study. For example, the nonnative species in this study were shade-tolerant understory species, which likely to have low horizontal leaf angles to capture light. Overstory canopy nonnative species could have higher leaf angles to avoid excessive radiation, therefore the leaf angles could be more similar to the ones of the native species. Furthermore, the generalization to the same species in other types of ecosystems may be also difficult, since plants can be physically and physiologically different among various ecosystems. Especially in Hawai‘i where its microclimate is different between the windward and the leeward sides of the islands and each island is isolated by ocean, plants can be different place to place.

The variability of the spectral properties over space and time needs to be considered. The modeled reflectance did not take account into shadows created between plants. The clumping effects of leaves would cause the spatial heterogeneity of canopy reflectance creating another source of variability. For more realistic simulations of canopy reflectance, a different model incorporating these features needs to be utilized. SPRINT (Spreading of Photons for Radiation INTerception) model by Goel and Thompson (2000) is one of those options. These complex models, however, require more rigorous detailed field measurements

Seasonal or even diurnal changes in plant physiology could cause changes in reflectance values. It was reported that *Coffea arabica* experienced some diurnal cycle of water stress giving the high water potential of leaves during mornings and low in afternoons (Barros *et al.* 1997). Since all the leaves were collected in afternoons, the high reflectance of coffee over the SWIR region can be explained by the water stress. Satellite images, however, are usually taken during mornings, suggesting the SWIR reflectance of coffee could be much lower than simulated. Such physiological differences of plants could increase the variability of the reflectance and decrease the separability among the species. It is, however, important to note that the temporal variability of reflectance by flowering or new leaves can create an opportunity to detect certain species.

The spatial resolution of the sensors to resolve surface features was not incorporated in this study. Even though the classification accuracy based on spectral differences were higher for ASTER and ETM+, the spatial resolutions of these sensors are 15m for the visible and NIR bands of ASTER and 30m for the SWIR bands of ASTER and all of the bands of ETM+. Minimal units of vegetation types in the Mākaha valley are often smaller than those spatial resolutions suggesting that ETM+ and ASTER will experience difficulties in detecting small patches of vegetation of interest when the images taken by those sensors are actually used. The high spatial resolution sensors, IKONOS and QuickBird however, have potentials of finding such patches even though they are limited with no SWIR bands. In such cases, the 80 % accuracies of the classification may be accurate enough for species detection.

Although some features influencing spectral properties of vegetation, such as shadows and spatial heterogeneity within canopy, were not incorporated, this study provide theoretical criteria of vegetation classification results to be expected with the four sensors. It can be expected that IKONOS and QuickBird will produce 80 % classification accuracies of vegetation. With ASTER and ETM+, 90 % classification accuracies can be expected even though their spatial resolutions would limit their capabilities of separating the species.

CHAPTER 5 CONCLUSION

All of the four multispectral sensors separated the native and nonnative plant species in Hawai'i spectrally suggesting the effectiveness of the remote sensing techniques in the invasive species management in Hawai'i. The sensors with the SWIR bands produced the higher accuracies of the separation although the trade off between the number of the spectral bands and the spatial resolution needs to be considered to utilize remote sensing techniques and satellite imagery effectively. It would probably be difficult to detect newly introduced species at early stages with these sensors, but it is very likely to be used for monitoring the spread of such species or the decline of the native species. On the other hand, the high spatial sensors may compensate the lack of SWIR bands by their abilities to resolve more detailed surface features, therefore may detect newly introduced species. It is important for resource managers to understand the abilities of sensors in order to meet their needs.

Table 1. The parameters for the canopy reflectance simulation

Parameters	Sample pool for each species	Selection	Note
Leaf Reflectance/ Transmittance	50 spectra	Random	Reflectance and transmittance were corresponding.
Bark Reflectance	15 spectra	Random	
Soil Reflectance	6 spectra	Random	
PAI	Values within minimum-maximum	Random	
LAI/NPVAI Fractions	Values within minimum-maximum	Random	The fractions were corresponding.
LAD/NPVAD	Values within ± 10% of mean	Random	Ellipsoidal inclination angle model was used to simulate the distribution from a selected mean.

Table 2. Spectral band widths for the four satellite sensors

Sensor	Blue	Green	Red	NIR	SWIR1	SWIR2				
ETM+	450-510	525-605	630-690	750-900	1550-1750	2080-2350				
ASTER		520-600	630-690	760-860	1600-1700	2145-2185	2185-2225	2235-2285	2295-2365	2360-2430
IKONOS	450-520	510-600	630-700	750-850						
QuickBird	450-520	520-600	630-690	760-900						

Table 3. Mean and standard deviation (sd) of PAI and leaf, NPV angles by species

	Koa	Lama	'Ōhia	Coffee	S.guava	C.berry
PAI mean	3.15	3.37	3.53	4.07	4.14	4.29
PAI sd	1.16	0.92	1.07	1.07	0.92	0.52
Leaf angle mean	69.95	33.92	42.90	20.92	22.48	22.07
Leaf angle sd	12.84	21.19	20.82	13.73	15.56	15.44
NPV angle mean	37.00	32.63	41.86	35.46	53.44	48.75
NPV angle sd	24.43	24.49	24.29	25.18	29.41	23.92

Table 4. Results of Maximum Likelihood for leaf scale reflectance classification
** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative)

(a) ASTER

Class	Koa*	Lama**	'Ōhia *	Coffee**	S.guava*	C.berry*	Total	User (%)	Commission (%)
Koa	50	0	1	0	0	0	51	98.04	1.96
Lama	0	50	0	0	0	0	50	100	0.00
'Ōhia	0	0	49	0	0	0	49	100	0.00
Coffee	0	0	0	50	0	0	50	100	0.00
S.guava	0	0	0	0	49	0	49	100	0.00
C.berry	0	0	0	0	1	50	51	98.04	1.96
Total	50	50	50	50	50	50	300		
Producer (%)	100.00	100.00	98.00	100.00	98.00	100.00		99.33 % (298/300)	
Omission (%)	0.00	0.00	2.00	0.00	2.00	0.00			

(b) ETM+

Class	Koa*	Lama	'Ōhia *	Coffee*	S.guava**	C.berry	Total	User (%)	Commission (%)
Koa	49	0	0	0	0	0	49	100.00	0.00
Lama	0	48	0	0	0	3	51	94.12	5.88
'Ōhia	1	0	50	0	0	0	51	98.04	1.96
Coffee	0	0	0	49	0	2	51	96.08	3.92
S.guava	0	0	0	0	50	0	50	100.00	0.00
C.berry	0	2	0	1	0	45	48	93.75	6.25
Total	50	50	50	50	50	50	300		
Producer (%)	98.00	96.00	100.00	98.00	100.00	90.00		97.00% (291/300)	
Omission (%)	2.00	4.00	0.00	2.00	0.00	10.00			

Table 4. (Continued) Results of Maximum Likelihood for leaf scale reflectance classification
** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative)

(c) IKONOS

Class	Koa	Lama	'Ōhia	Coffee	S.guava**	C.berry	Total	User (%)	Commission (%)
Koa	47	0	0	2	0	0	49	95.92	4.08
Lama	0	47	0	1	0	3	51	92.16	7.84
'Ōhia	1	0	45	1	0	4	51	88.24	11.77
Coffee	2	0	5	44	0	4	55	80.00	20.00
S.guava	0	0	0	0	50	0	50	100.00	0.00
C.berry	0	3	0	2	0	39	44	88.64	11.36
Total	50	50	50	50	50	50	300		
Producer (%)	94.00	94.00	90.00	88.00	100.00	78.00		90.67% (272/300)	
Omission (%)	6.00	6.00	10.00	12.00	0.00	22.00			

(d) QuickBird

Class	Koa	Lama	'Ōhia	Coffee	S.guava	C.berry	Total	User (%)	Commission (%)
Koa	47	0	0	2	0	0	49	95.92	4.08
Lama	0	48	0	1	1	3	53	90.57	9.43
'Ōhia	1	0	50	1	0	3	55	90.91	9.09
Coffee	2	0	0	45	0	4	51	88.24	11.77
S.guava	0	0	0	0	49	0	49	100.00	0.00
C.berry	0	2	0	1	0	40	43	93.02	6.98
Total	50	50	50	50	50	50	300		
Producer (%)	94.00	96.00	100.00	90.00	98.00	80.00		93.00% (279/300)	
Omission (%)	6.00	4.00	0.00	10.00	2.00	20.00			

Table 5. Results of Maximum Likelihood for leaf scale transmittance classification
** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative)

(a) ASTER

Class	Koa	Lama	‘Ōhia	Coffee	S.guava	C.berry	Total	User (%)	Commission (%)
Koa	49	0	0	0	0	0	49	100.00	0.00
Lama	0	50	0	0	0	0	50	100.00	0.00
‘Ōhia	1	0	50	0	0	0	51	98.04	1.96
Coffee	0	0	0	48	0	2	50	96.00	4.00
S.guava	0	0	0	0	50	0	50	100.00	0.00
C.berry	0	0	0	2	0	48	50	96.00	4.00
Total	50	50	50	50	50	50	300		
Producer (%)	98.00	100.00	100.00	96.00	100.00	96.00		98.33% (295/300)	
Omission (%)	2.00	0.00	0.00	4.00	0.00	4.00			

(b) ETM+

Class	Koa	Lama	‘Ōhia	Coffee	S.guava	C.berry	Total	User (%)	Commission (%)
Koa	49	0	0	0	0	0	49	100.00	0.00
Lama	0	50	1	0	0	0	51	98.04	1.96
‘Ōhia	1	0	49	0	0	0	50	98.00	2.00
Coffee	0	0	0	48	0	1	49	97.96	2.04
S.guava	0	0	0	0	49	0	49	100.00	0.00
C.berry	0	0	0	2	1	49	52	94.23	5.77
Total	50	50	50	50	50	50	300		
Producer (%)	98.00	100.00	98.00	96.00	98.00	98.00		98.00% (294/300)	
Omission (%)	2.00	0.00	2.00	4.00	2.00	2.00			

Table 5. (Continued)Results of Maximum Likelihood for leaf scale transmittance classification
** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative)

(c) IKONOS

Class	Koa	Lama	'Ōhia	Coffee	S.guava	C.berry	Total	User(%)	Commission (%)
Koa	49	0	0	0	0	0	49	100.00	0.00
Lama	0	50	1	0	0	0	51	98.04	1.96
'Ōhia	1	0	49	0	0	0	50	98.00	2.00
Coffee	0	0	0	48	0	5	53	90.57	9.43
S.guava	0	0	0	1	48	0	49	97.96	2.04
C.berry	0	0	0	1	2	45	48	93.75	6.25
Total	50	50	50	50	50	50	300		
Producer (%)	98.00	100.00	98.00	96.00	96.00	90.00		96.33% (289/300)	
Omission (%)	2.00	0.00	2.00	4.00	4.00	10.00			

(d) Quickbird

Class	Koa	Lama	'Ōhia	Coffee	S.guava	C.berry	Total	User (%)	Commission (%)
Koa	49	0	0	0	0	0	49	100.00	0.00
Lama	0	50	1	0	0	0	51	98.04	1.96
'Ōhia	1	0	49	0	0	0	50	98.00	2.00
Coffee	0	0	0	48	0	4	52	92.31	7.69
S.guava	0	0	0	1	48	0	49	97.96	2.04
C.berry	0	0	0	1	2	46	49	93.88	6.12
Total	50	50	50	50	50	50	300		
Producer (%)	98.00	100.00	98.00	96.00	96.00	92.00		96.67% (290/300)	
Omission (%)	2.00	0.00	2.00	4.00	4.00	8.00			

Table 6. Results of Maximum likelihood for canopy scale reflectance classification

** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative)

(a) ASTER

Class	Koa	Lama	ʻŌhia	Coffee	S.guava	C.berry	Total	User (%)	Commission (%)
Koa	9883	0	202	0	0	12	10097	97.88	2.12
Lama	2	9106	81	4	0	814	10007	91.00	9.00
ʻŌhia	86	0	9420	0	0	39	9545	98.69	1.31
Coffee	0	14	0	9944	0	102	10060	98.85	1.15
S.guava	0	0	153	0	10000	28	10181	98.22	1.78
C.berry	29	880	144	52	0	9005	10110	89.07	10.93
Total	10000	10000	10000	10000	10000	10000	60000		
Producer (%)	98.83	91.06	94.2	99.44	100.00	90.05		95.60% (57358/60000)	
Omission (%)	1.17	8.94	5.80	0.56	0.00	9.95			

(b) ETM+

Class	Koa	Lama	ʻŌhia	Coffee	S.guava	C.berry	Total	User (%)	Commission (%)
Koa	9635	0	322	0	0	11	9968	96.66	3.34
Lama	0	9170	94	0	0	658	9922	92.42	7.58
ʻŌhia	321	12	9299	0	4	186	9822	94.68	5.32
Coffee	0	0	0	9950	0	199	10149	98.04	1.96
S.guava	1	0	113	0	9996	19	10129	98.69	1.31
C.berry	43	818	172	50	0	8927	10010	89.18	10.82
Total	10000	10000	10000	10000	10000	10000	60000		
Producer (%)	96.35	91.70	92.99	99.5	99.96	89.27		94.96% (56977/60000)	
Omission (%)	3.65	8.30	7.01	0.50	0.04	10.73			

Table 6. (Continued) Results of Maximum likelihood for canopy scale reflectance classification
** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative)

(c) IKONOS

Class	Koa	Lama	ʻŌhia	Coffee	S.guava	C.berry	Total	User (%)	Commission (%)
Koa	8872	80	1901	0	0	267	11120	79.78	20.22
Lama	59	8728	86	74	0	1094	10041	86.92	13.08
ʻŌhia	960	0	6045	57	47	602	7711	78.40	21.60
Coffee	1	40	26	8224	563	173	9027	91.11	8.90
S.guava	0	3	233	1388	8970	884	11478	78.15	21.85
C.berry	108	1149	1709	257	420	6980	10623	65.71	34.29
Total	10000	10000	10000	10000	10000	10000	60000		
Producer (%)	88.72	87.28	60.45	82.24	89.70	69.80		79.70% (47819/60000)	
Omission (%)	11.28	12.72	39.55	17.76	10.30	30.20			

(d) Quickbird

Class	Koa	Lama	ʻŌhia	Coffee	S.guava	C.berry	Total	User (%)	Commission (%)
Koa	8873	60	2034	0	0	202	11169	79.44	20.56
Lama	51	8601	123	87	0	1029	9891	86.96	13.04
ʻŌhia	1009	0	5877	52	44	654	7636	76.96	23.04
Coffee	1	72	25	7984	610	200	8892	89.79	10.21
S.guava	0	0	255	1577	9038	709	11579	78.06	21.94
C.berry	66	1267	1686	300	308	7206	10833	66.52	33.48
Total	10000	10000	10000	10000	10000	10000	60000		
Producer (%)	88.73	86.01	58.77	79.84	90.38	72.06		79.30% (47579/60000)	
Omission (%)	11.27	13.99	41.23	20.16	9.62	27.94			

Table 7. Results of t-test for leaf reflectance

A indicates the species different from all the other species. B indicates the species different from the species from another group (invasive or native). C indicates the species mixed with one or more species from the other group, therefore inseparable.

(a) Blue bands

Sensor	Koa	Lama	'Ohia	Coffee	S.guava	C.berry
ASTER	N/A	N/A	N/A	N/A	N/A	N/A
ETM+	C	A	B	C	B	B
IKONOS	B	A	B	A	B	B
QuickBird	B	A	B	A	B	B

(b) Green bands

Sensor	Koa	Lama	'Ohia	Coffee	S.guava	C.berry
ASTER	A	A	C	C	B	B
ETM+	A	A	C	C	B	B
IKONOS	A	A	C	C	A	A
QuickBird	A	A	C	C	B	B

(c) Red bands

Sensor	Koa	Lama	'Ohia	Coffee	S.guava	C.berry
ASTER	A	A	C	C	B	B
ETM+	A	A	C	C	B	B
IKONOS	A	A	C	C	A	A
QuickBird	A	A	C	C	B	B

(d) NIR bands

Sensor	Koa	Lama	'Ohia	Coffee	S.guava	C.berry
ASTER	B	C	B	C	A	C
ETM+	B	C	B	C	A	C
IKONOS	B	C	B	C	A	C
QuickBird	B	C	B	C	A	C

(e) SWIR1 bands

Sensor	Koa	Lama	'Ohia	Coffee	S.guava	C.berry
ASTER	B	C	B	A	C	C
ETM+	B	C	B	A	C	C
IKONOS	N/A	N/A	N/A	N/A	N/A	N/A
QuickBird	N/A	N/A	N/A	N/A	N/A	N/A

(f) SWIR 2 bands

Sensor	Koa	Lama	'Ohia	Coffee	S.guava	C.berry
ASTER1	B	C	B	A	C	C
ASTER2	B	C	B	A	C	C
ASTER3	A	C	A	A	C	C
ASTER4	B	C	B	A	B	C
ASTER5	B	B	B	A	B	B
ETM+	B	C	B	A	C	C
IKONOS	N/A	N/A	N/A	N/A	N/A	N/A
QuickBird	N/A	N/A	N/A	N/A	N/A	N/A

(g) NDVI

Sensor	Koa	Lama	'Ohia	Coffee	S.guava	C.berry
ASTER	A	A	C	A	C	A
ETM+	C	A	C	C	C	A
IKONOS	A	A	C	A	C	A
QuickBird	A	A	C	A	C	A

Table 8. Results of t-test for leaf transmittance

A indicates the species different from all the other species. B indicates the species different from the species from another group (invasive or native). C indicates the species mixed with one or more species from the other group, therefore inseparable.

(a) Blue bands

Sensor	Koa	Lama	'Ohia	Coffee	S.guava	C.berry
ASTER	N/A	N/A	N/A	N/A	N/A	N/A
ETM+	C	B	B	B	A	C
IKONOS	C	B	B	C	A	C
QuickBird	C	B	B	C	A	C

(b) Green bands

Sensor	Koa	Lama	'Ohia	Coffee	S.guava	C.berry
ASTER	A	C	A	C	A	C
ETM+	A	C	A	C	A	C
IKONOS	A	C	A	C	A	C
QuickBird	A	C	A	C	A	C

(c) Red bands

Sensor	Koa	Lama	'Ohia	Coffee	S.guava	C.berry
ASTER	C	A	A	C	A	C
ETM+	C	A	A	C	A	C
IKONOS	C	A	A	C	A	C
QuickBird	C	A	A	C	A	C

(d) NIR bands

Sensor	Koa	Lama	'Ohia	Coffee	S.guava	C.berry
ASTER	A	C	C	C	C	A
ETM+	A	C	C	C	C	A
IKONOS	A	C	C	C	C	A
QuickBird	A	C	C	C	C	A

(e) SWIR1 bands

Sensor	Koa	Lama	'Ohia	Coffee	S.guava	C.berry
ASTER	C	A	A	A	A	C
ETM+	C	A	A	A	A	C
IKONOS	N/A	N/A	N/A	N/A	N/A	N/A
QuickBird	N/A	N/A	N/A	N/A	N/A	N/A

(f) SWIR 2 bands

Sensor	Koa	Lama	'Ohia	Coffee	S.guava	C.berry
ASTER1	A	B	B	A	A	A
ASTER2	A	B	B	A	A	A
ASTER3	B	B	B	A	A	A
ASTER4	B	B	B	A	A	A
ASTER5	B	B	B	A	A	A
ETM+	A	B	B	A	A	A
IKONOS	N/A	N/A	N/A	N/A	N/A	N/A
QuickBird	N/A	N/A	N/A	N/A	N/A	N/A

Table 9. Results of t-test for canopy reflectance
A indicates the species different from all the other species. B indicates the species different from the species from another group (invasive or native). C indicates the species mixed with one or more species from the other group, therefore inseparable.

(a) Blue bands

Sensor	Koa	Lama	'Ōhia	Coffee	S.guava	C.berry
ASTER	N/A	N/A	N/A	N/A	N/A	N/A
ETM+	C	C	C	C	C	C
IKONOS	B	C	C	A	B	C
QuickBird	B	C	C	B	C	C

(b) Green bands

Sensor	Koa	Lama	'Ōhia	Coffee	S.guava	C.berry
ASTER	A	C	A	C	C	C
ETM+	A	C	A	C	C	C
IKONOS	A	C	B	A	B	C
QuickBird	A	C	A	B	C	C

(c) Red bands

Sensor	Koa	Lama	'Ōhia	Coffee	S.guava	C.berry
ASTER	C	C	C	C	C	C
ETM+	C	C	A	C	C	C
IKONOS	C	C	C	C	C	C
QuickBird	C	C	C	C	C	C

(d) NIR bands

Sensor	Koa	Lama	'Ōhia	Coffee	S.guava	C.berry
ASTER	B	B	B	B	B	A
ETM+	B	B	B	B	B	A
IKONOS	B	B	B	B	B	A
QuickBird	B	B	B	B	B	A

(e) SWIR 1 bands

Sensor	Koa	Lama	'Ōhia	Coffee	S.guava	C.berry
ASTER	C	C	C	A	C	C
ETM+	C	C	C	A	C	C
IKONOS	N/A	N/A	N/A	N/A	N/A	N/A
QuickBird	N/A	N/A	N/A	N/A	N/A	N/A

(f) SWIR 2 bands

Sensor	Koa	Lama	'Ōhia	Coffee	S.guava	C.berry
ASTER1	C	B	C	C	A	C
ASTER2	A	B	B	A	A	A
ASTER3	C	B	C	C	C	A
ASTER4	C	B	C	C	C	C
ASTER5	C	C	C	C	C	C
ETM+	A	B	C	C	A	A
IKONOS	N/A	N/A	N/A	N/A	N/A	N/A
QuickBird	N/A	N/A	N/A	N/A	N/A	N/A

(g) NDVI

Sensor	Koa	Lama	'Ōhia	Coffee	S.guava	C.berry
ASTER	C	B	B	B	B	C
ETM+	B	B	B	B	B	A
IKONOS	C	B	B	B	B	C
QuickBird	C	B	B	B	B	C

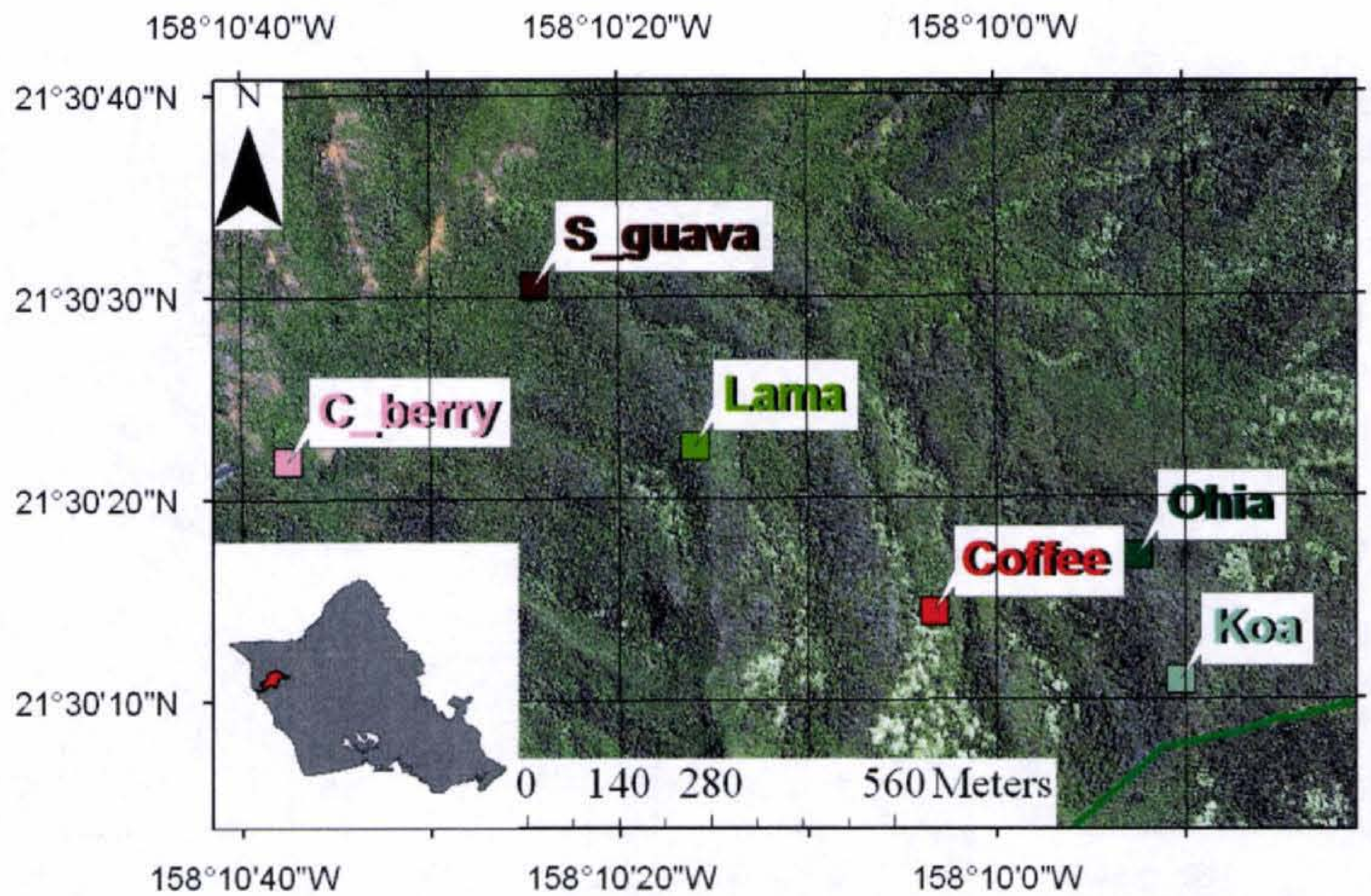

Figure 1. Plot locations across the valley.

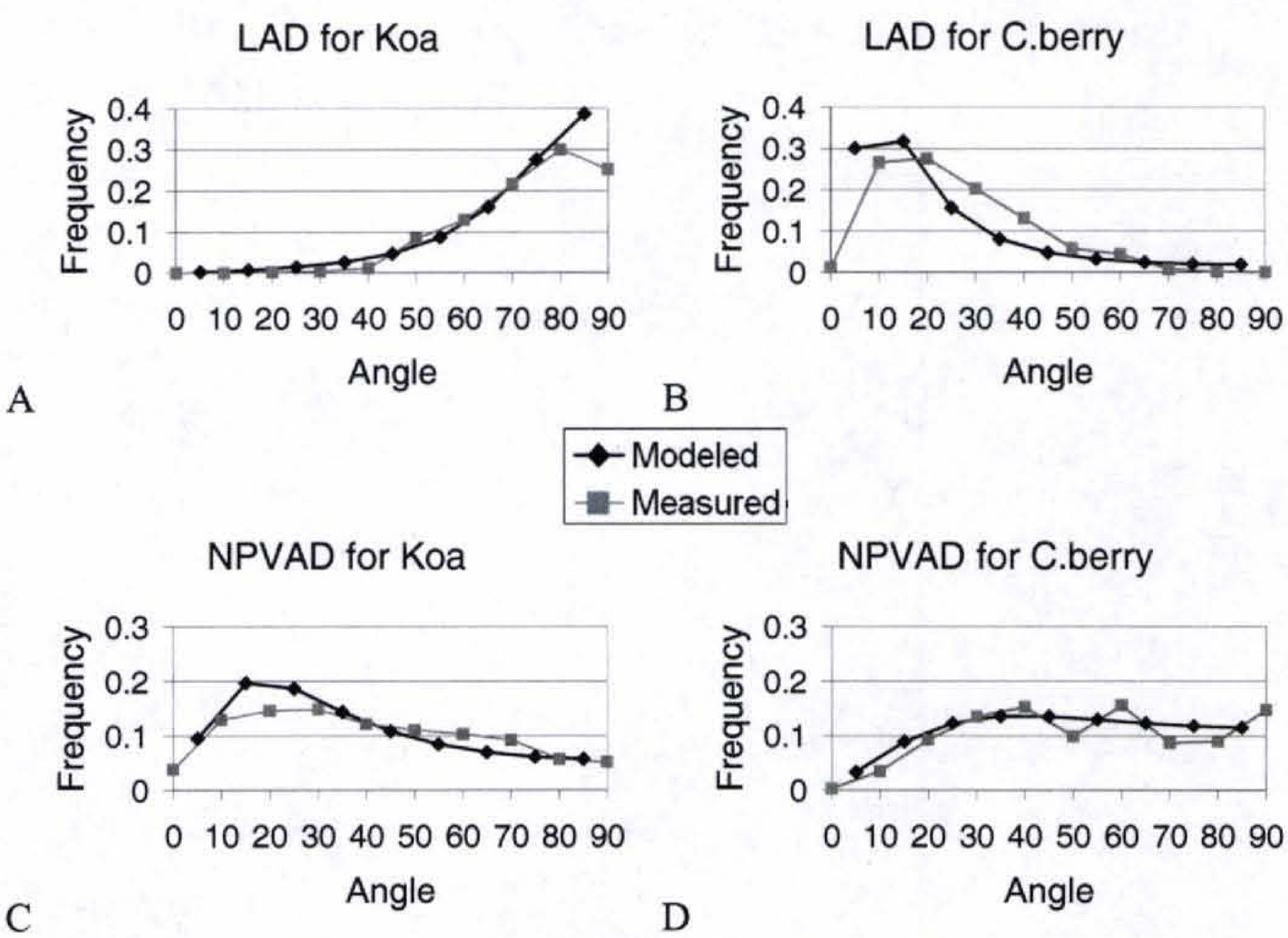

Figure 2. Examples of modeled and measured leaf and NPV angle distribution.
Ellipsoidal leaf inclination model was used for the simulation. The data were normalized.

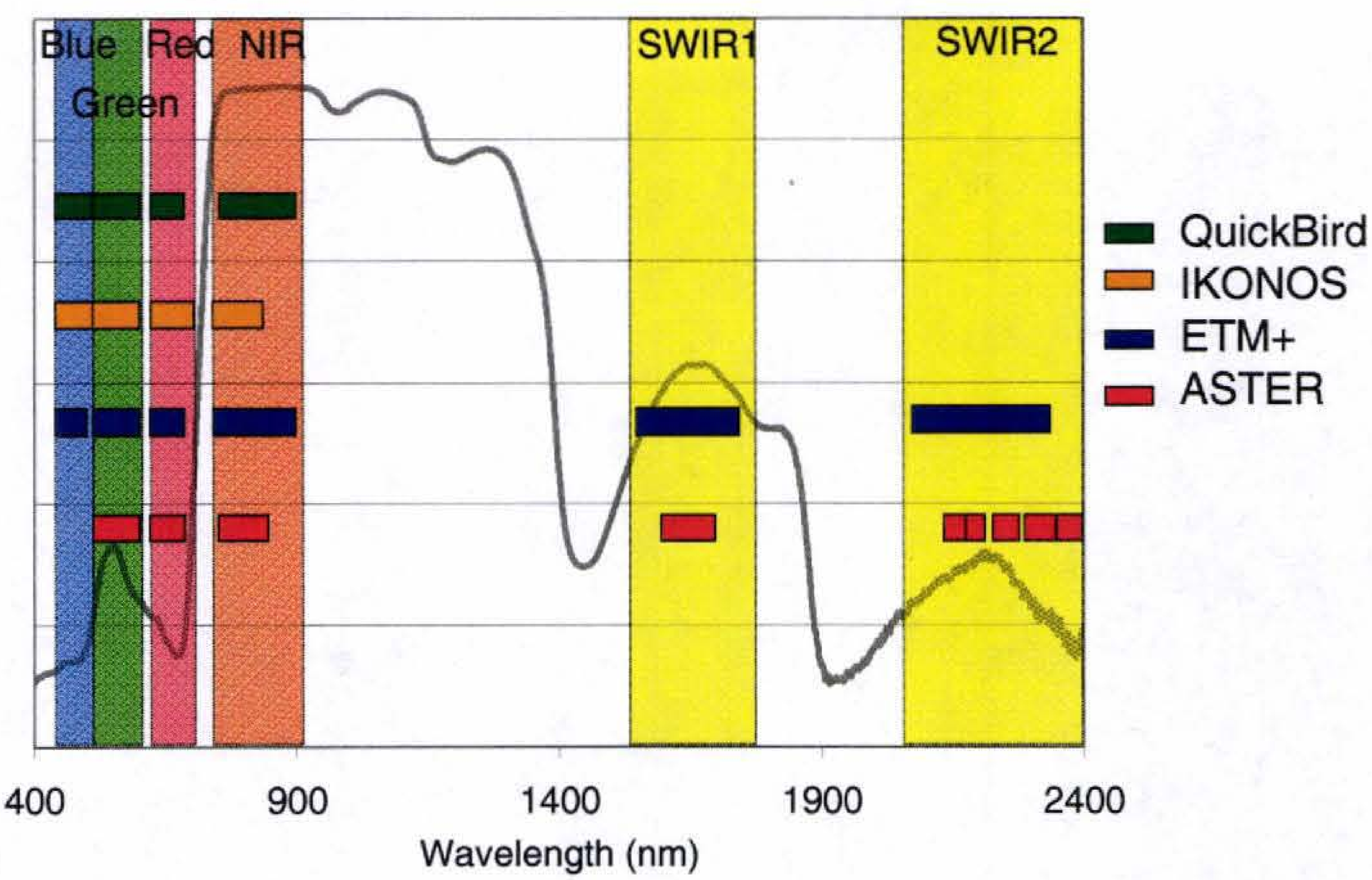

Figure 3. Band locations of the sensors.

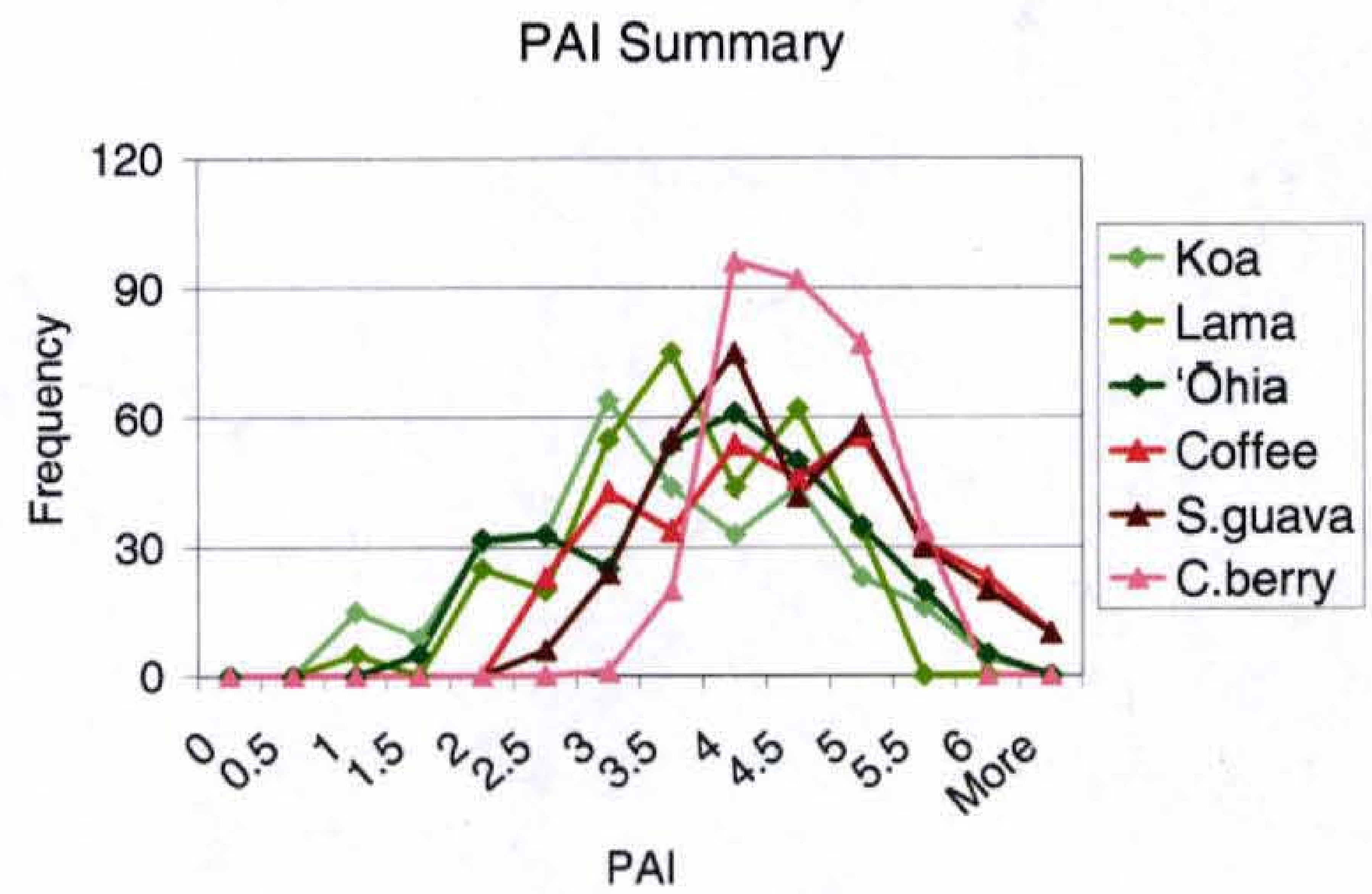

Figure 4. Plant Area Index by species.

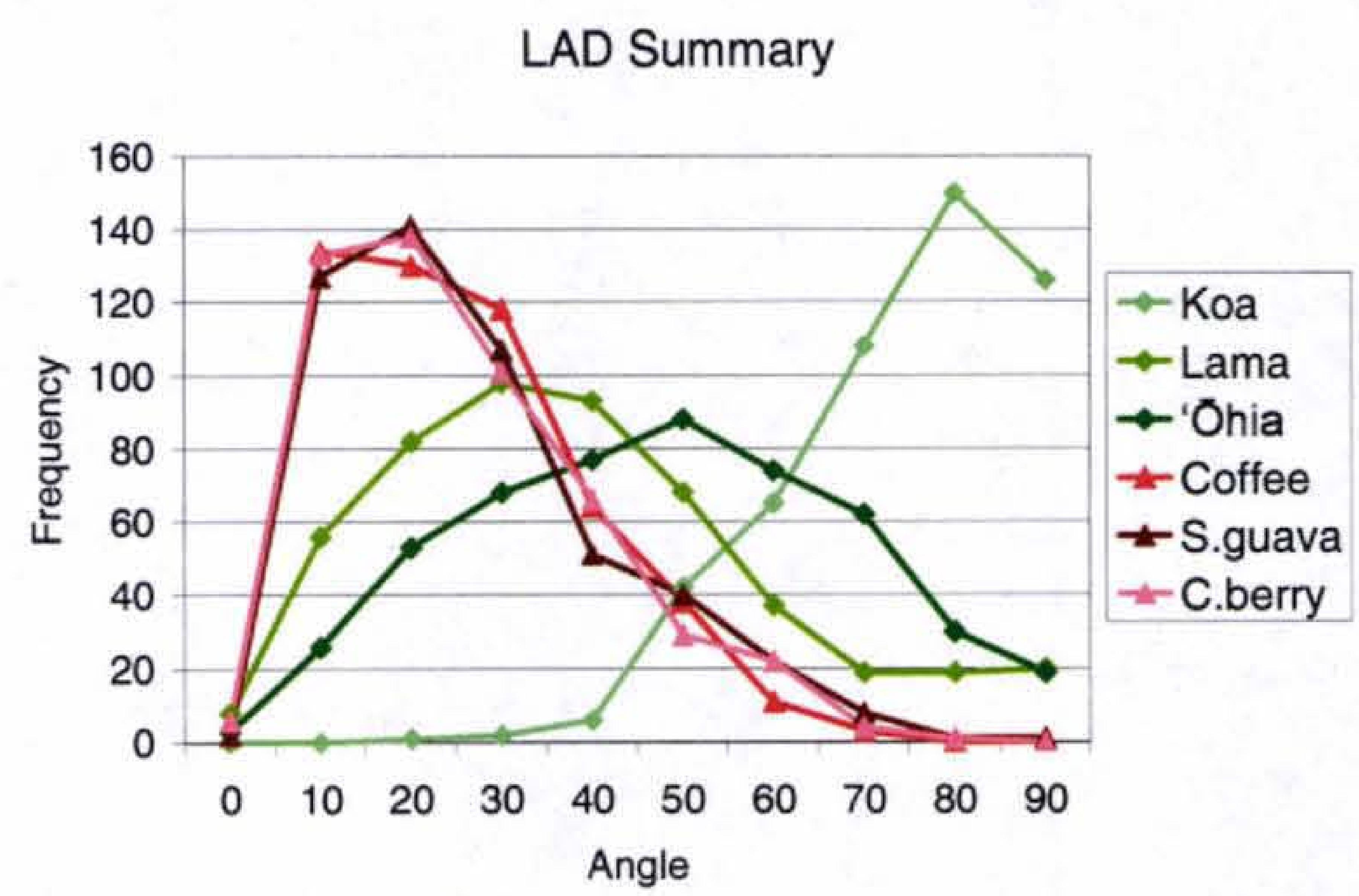

Figure 5. Leaf Angle Distribution by species.

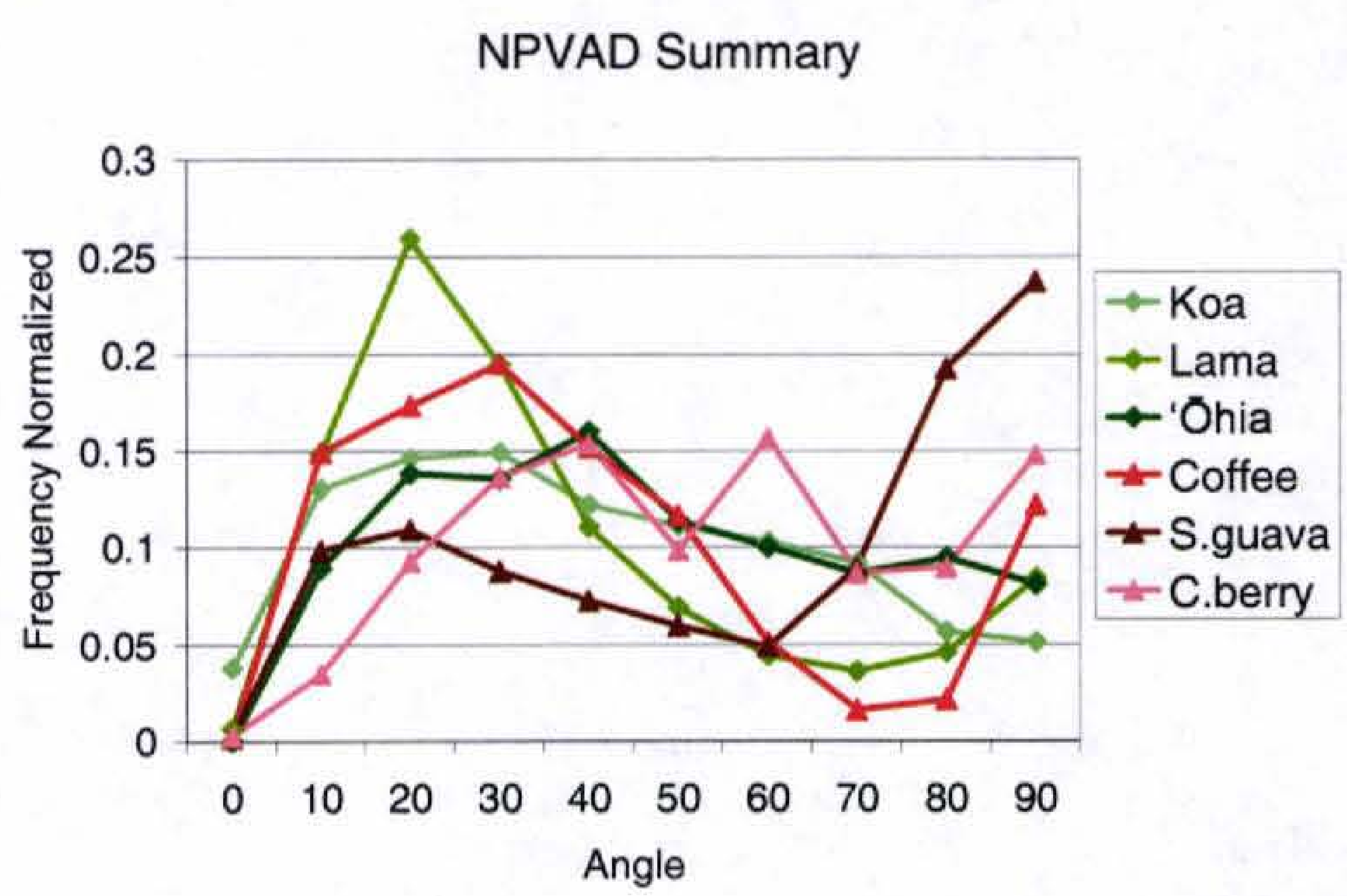

Figure 6. Non-photosynthetic Active Vegetation Angle Distribution by species.
Due to the differences in the sample sizes among the species, the results were normalized.

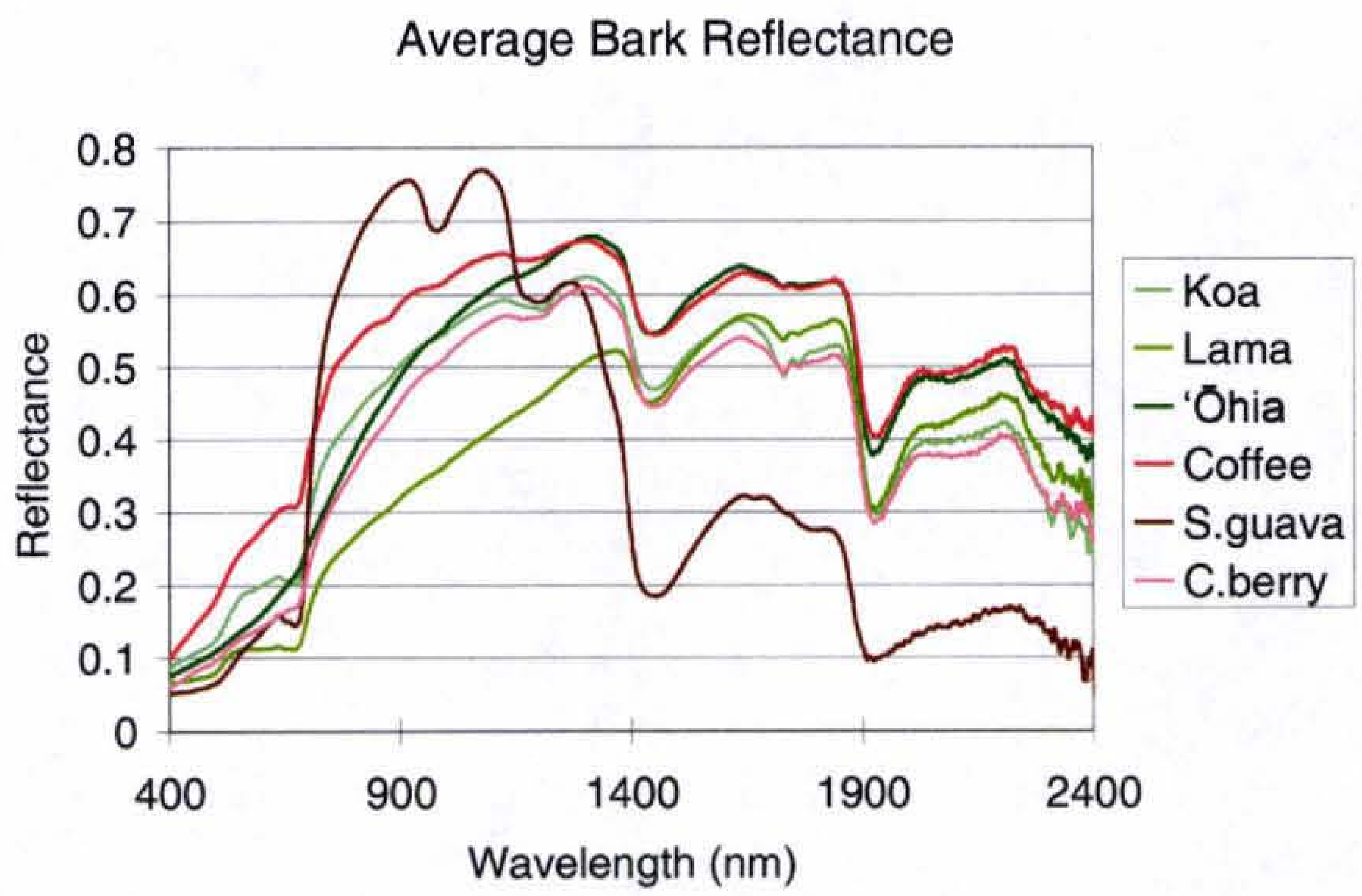

Figure 7. Mean hyperspectral bark reflectance.

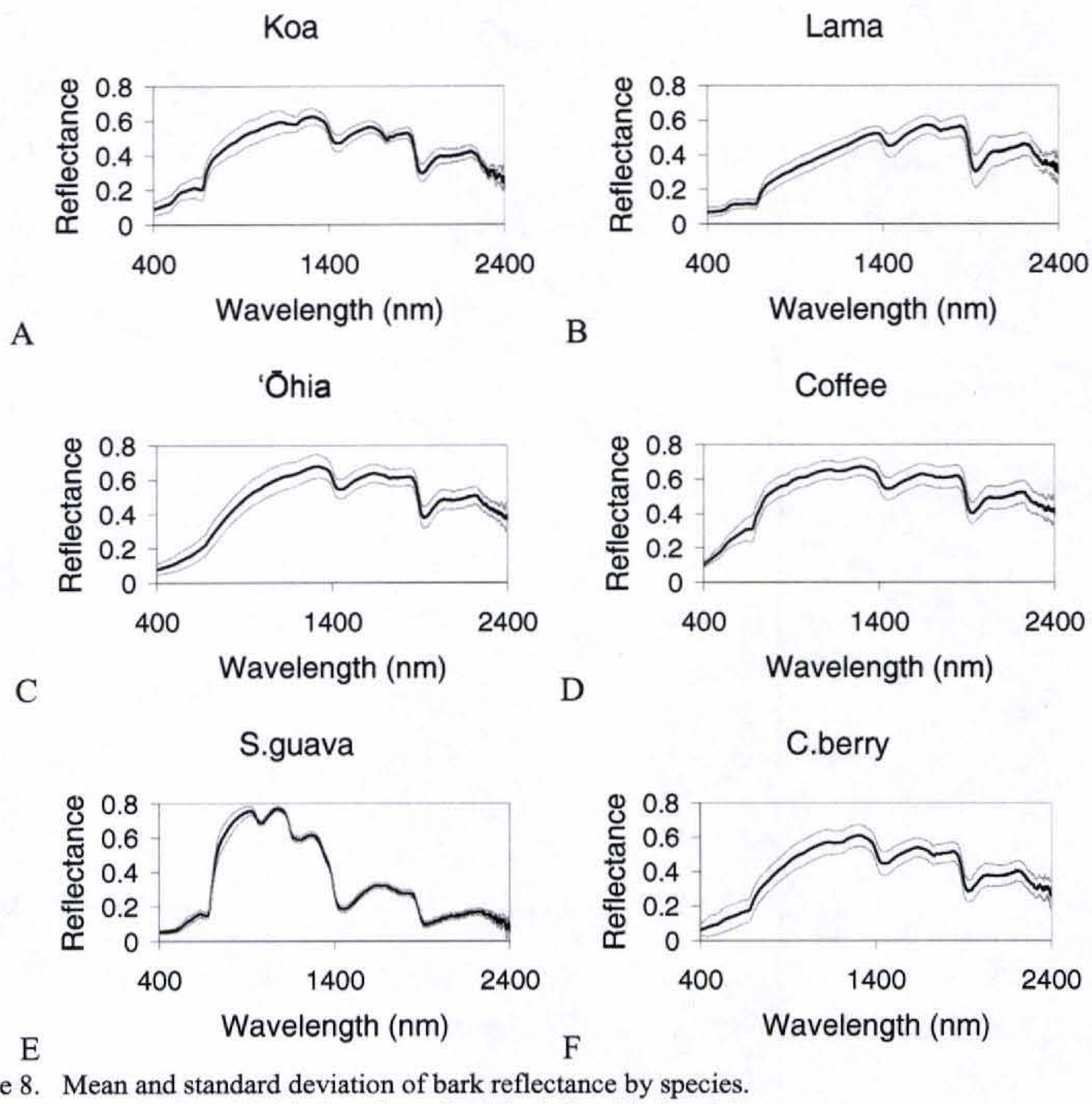

Figure 8. Mean and standard deviation of bark reflectance by species.
Mean displayed in black and standard deviation displayed in gray.

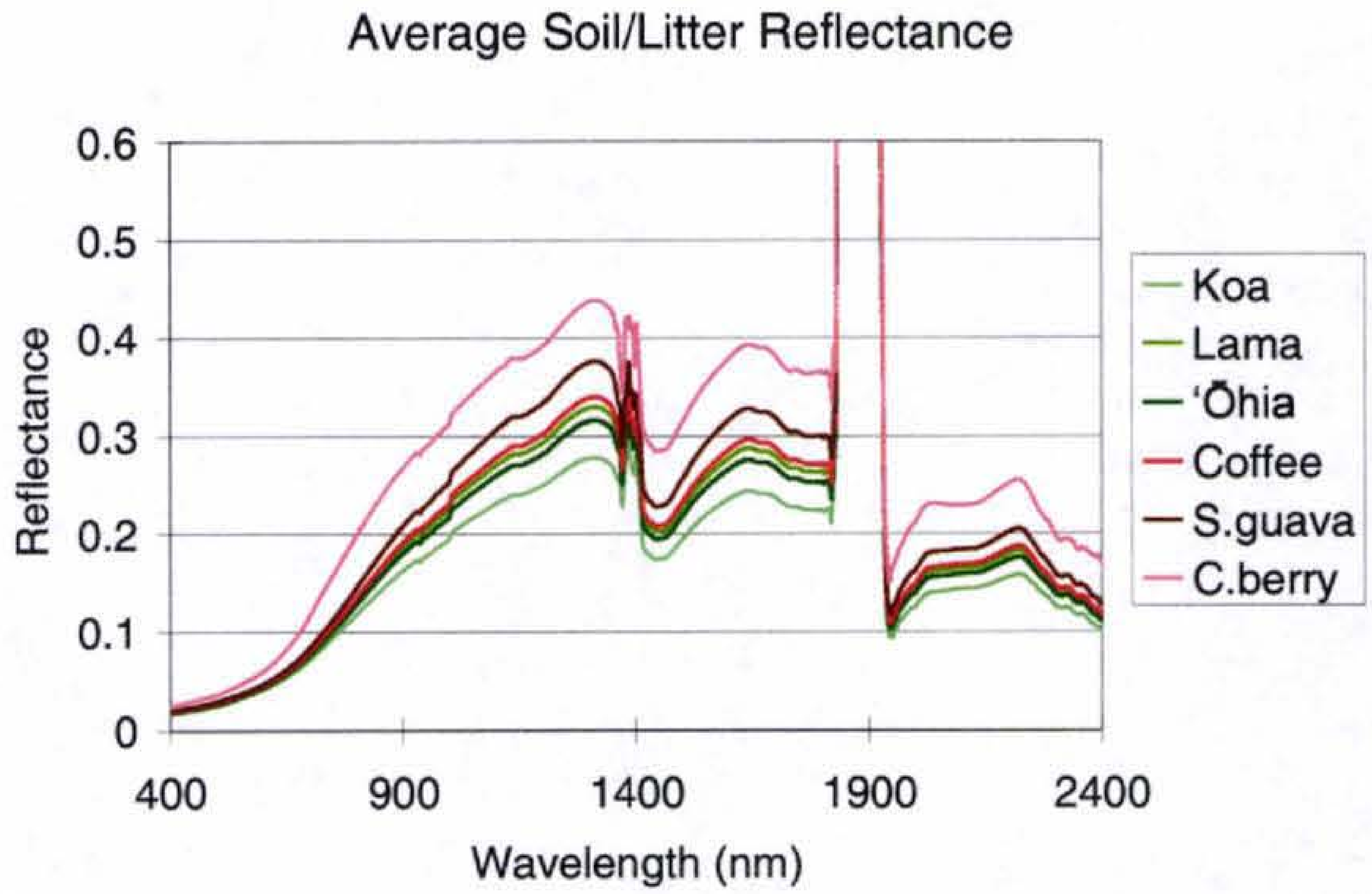

Figure 9. Mean hyperspectral soil/litter reflectance.

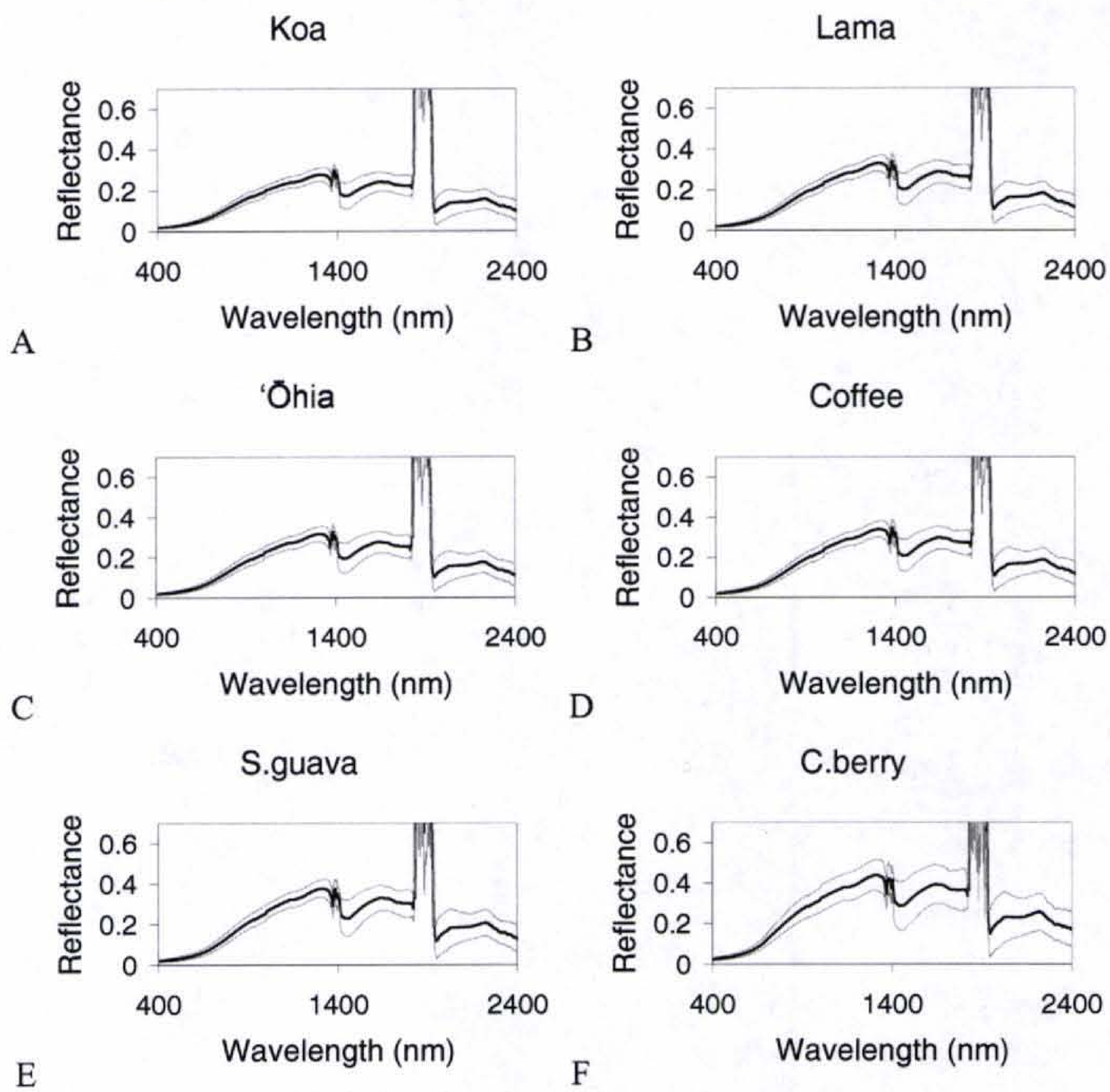

Figure 10. Mean and standard deviation of soil/litter reflectance by species.
Mean displayed in black and standard deviation displayed in gray.

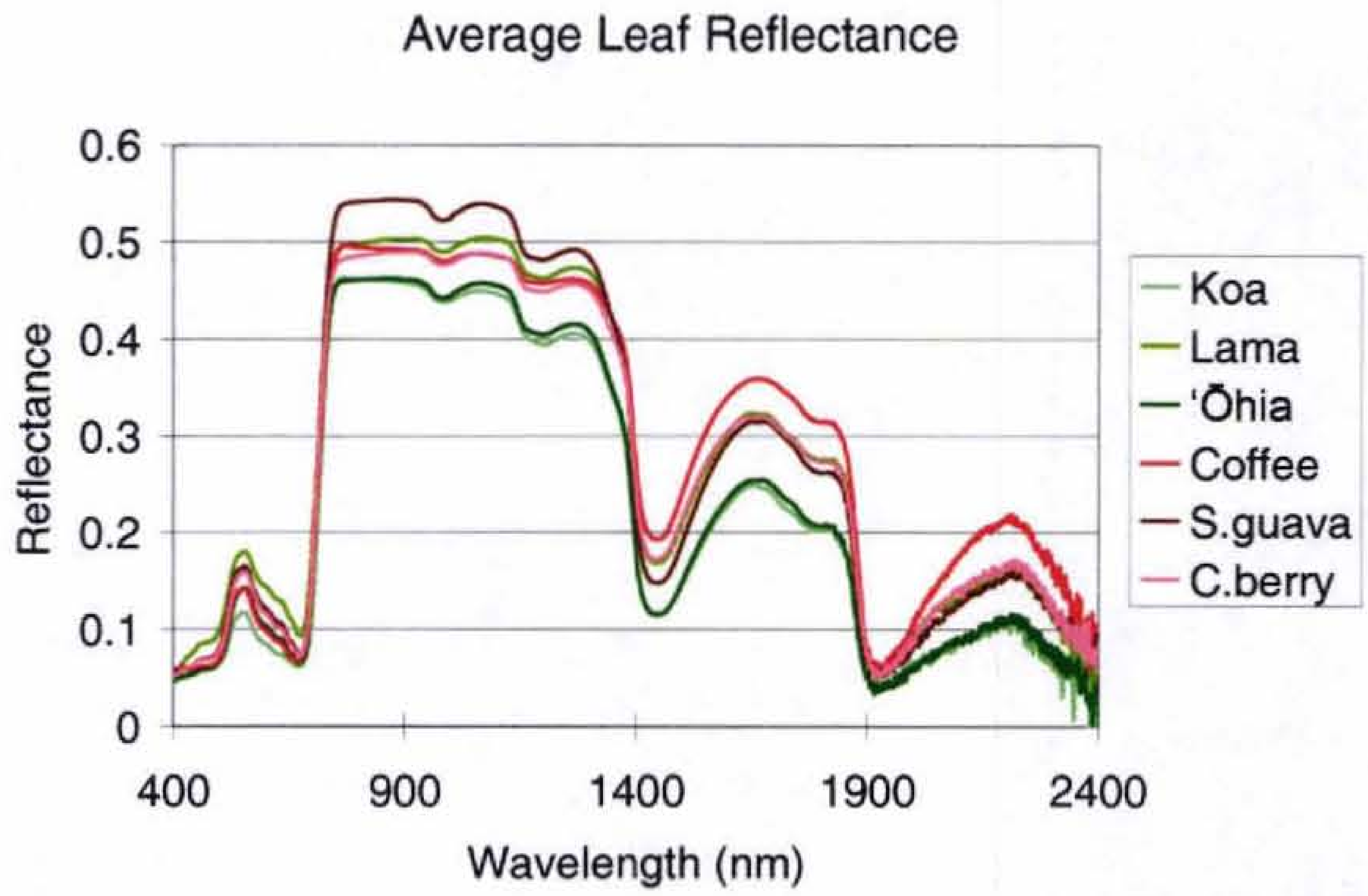

Figure 11. Mean hyperspectral leaf reflectance.

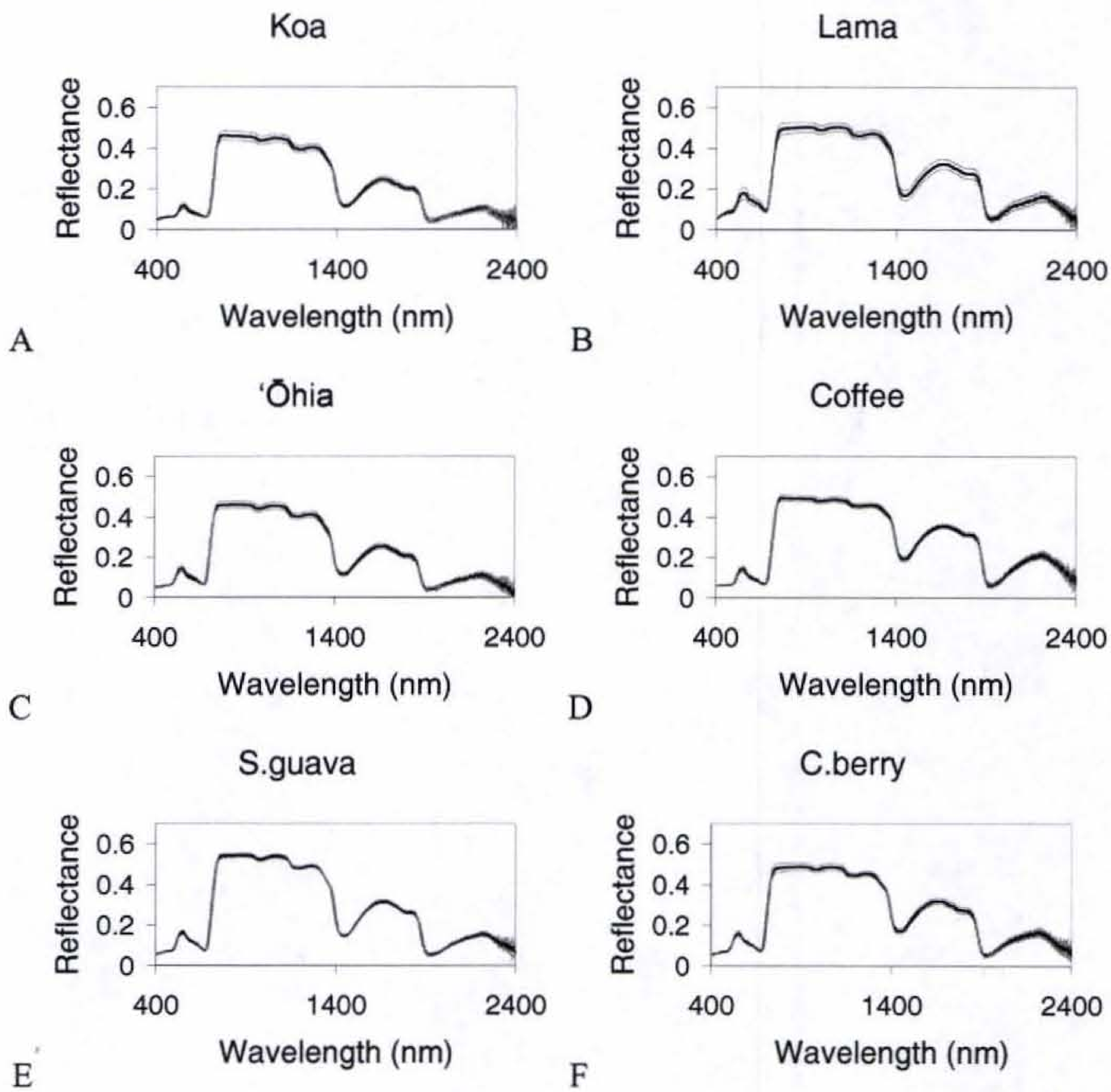

Figure 12. Mean and standard deviation of leaf reflectance by species.
Mean displayed in black and standard deviation displayed in gray.

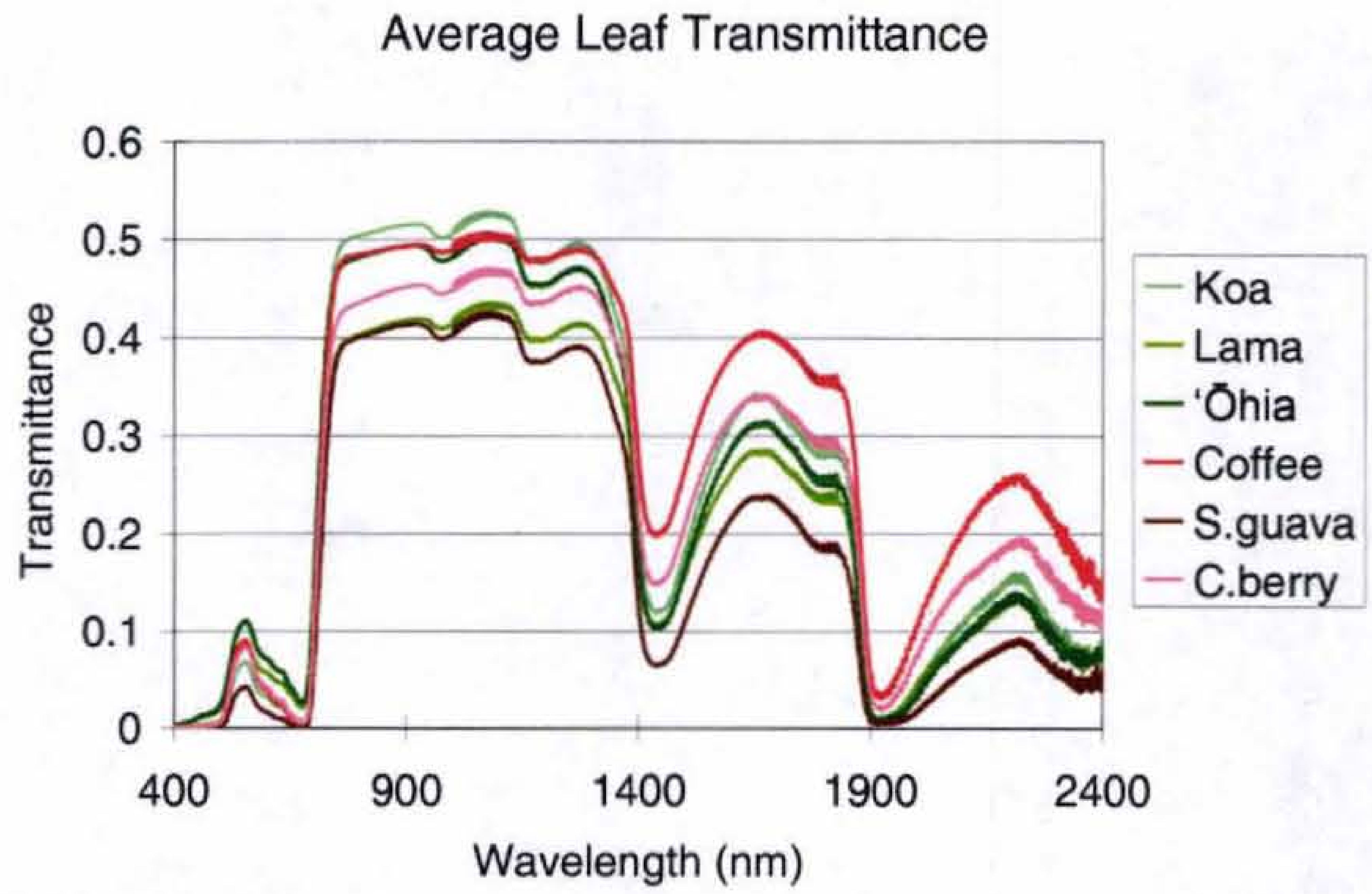

Figure 13. Mean hyperspectral leaf transmittance.

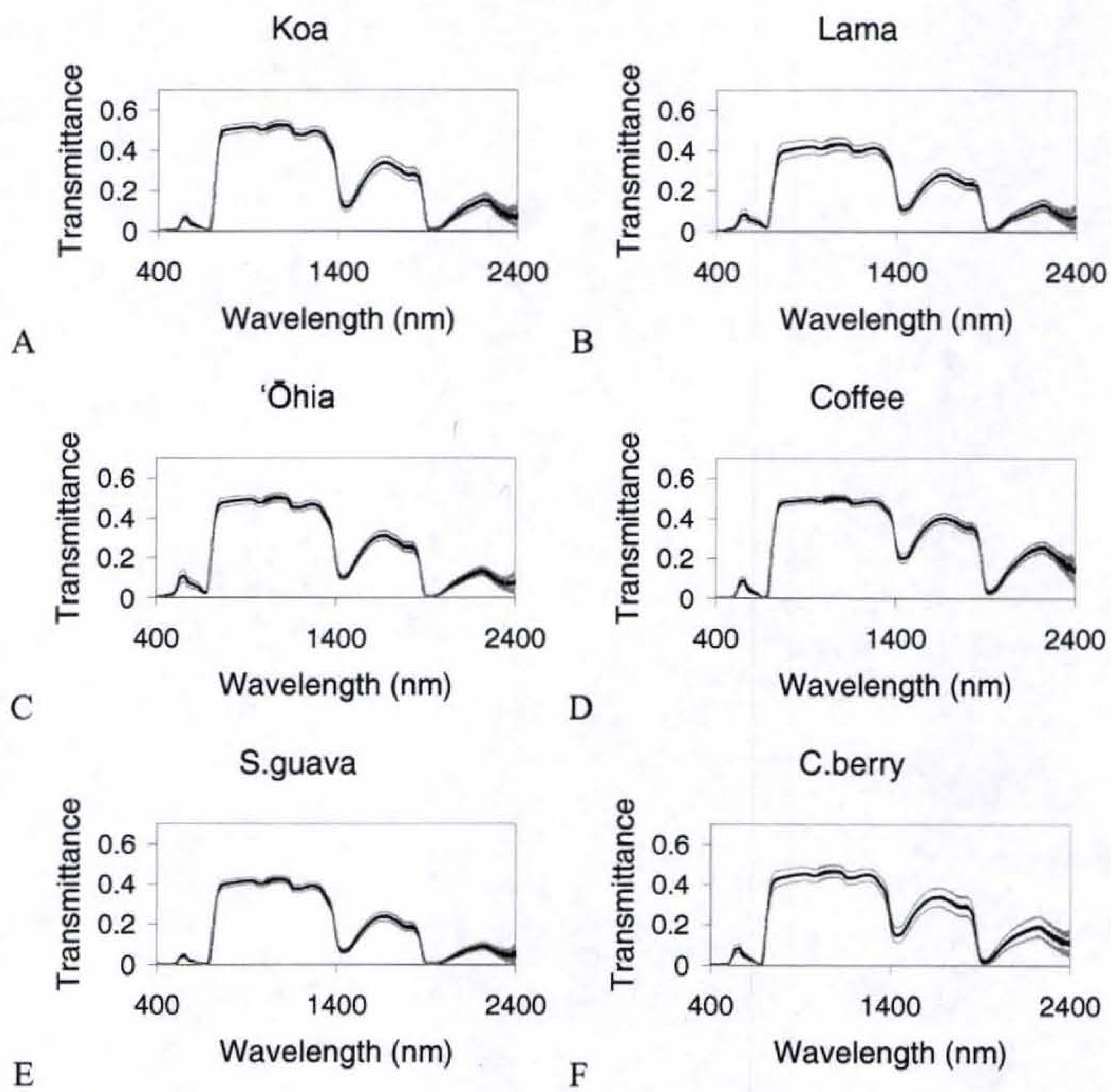

Figure 14. Mean and standard deviation of leaf transmittance by species.
Mean displayed in black and standard deviation displayed in gray.

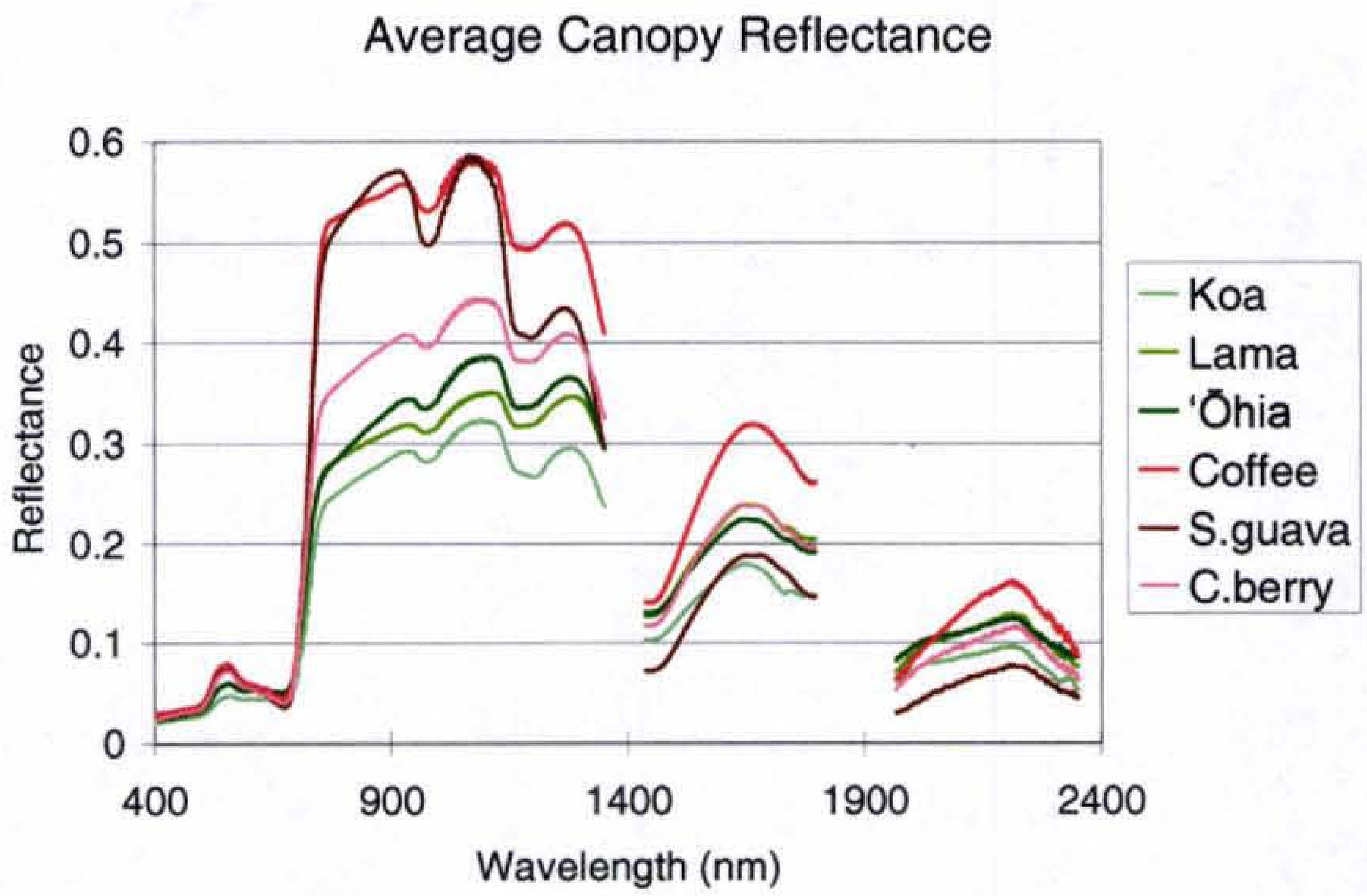

Figure 15. Mean hyperspectral canopy reflectance.

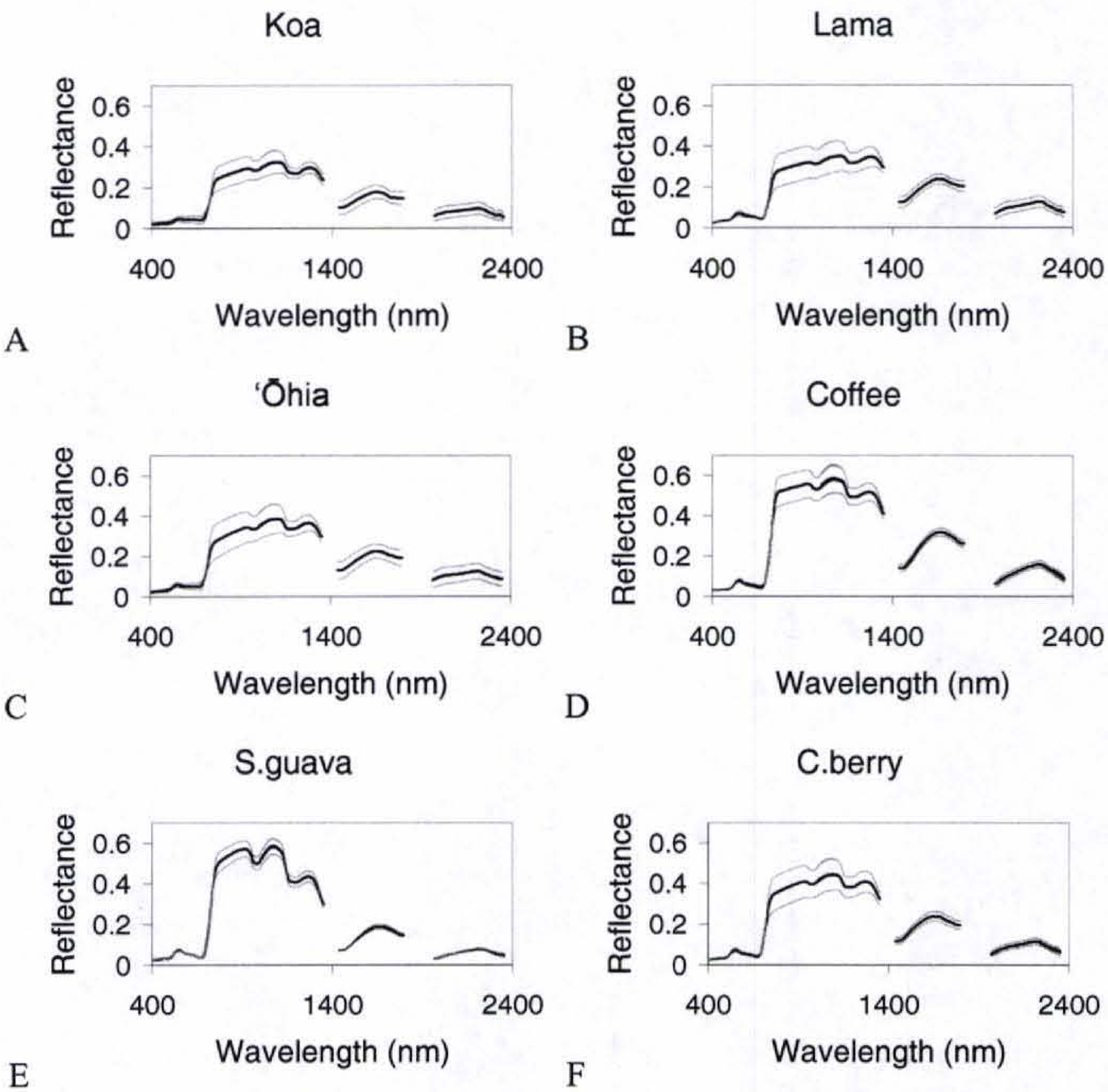

Figure 16. Mean and standard deviation of canopy reflectance by species.
Mean displayed in black and standard deviation displayed in gray.

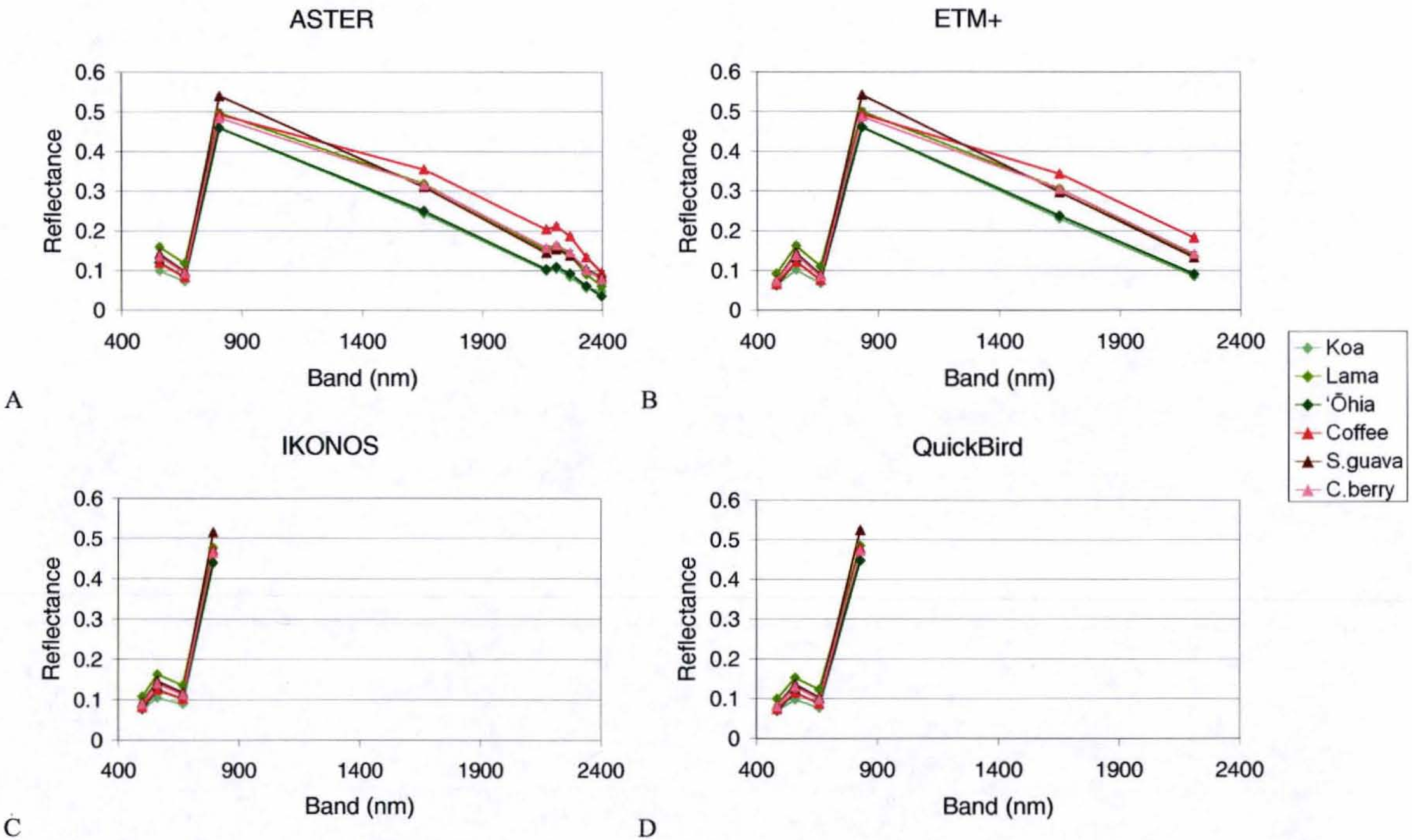

Figure 17. Mean multispectral leaf reflectance.

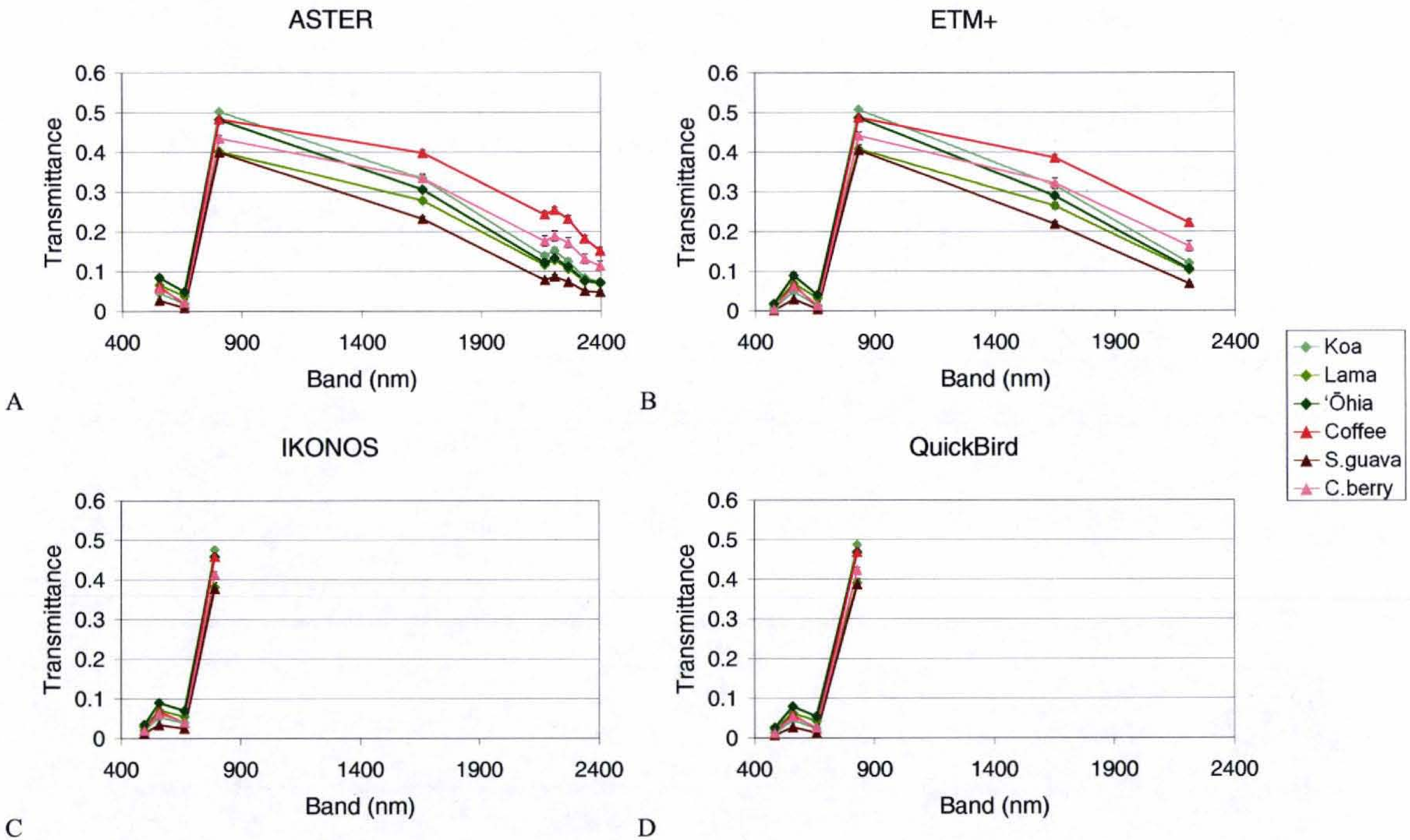

Figure 18. Mean multispectral leaf transmittance.

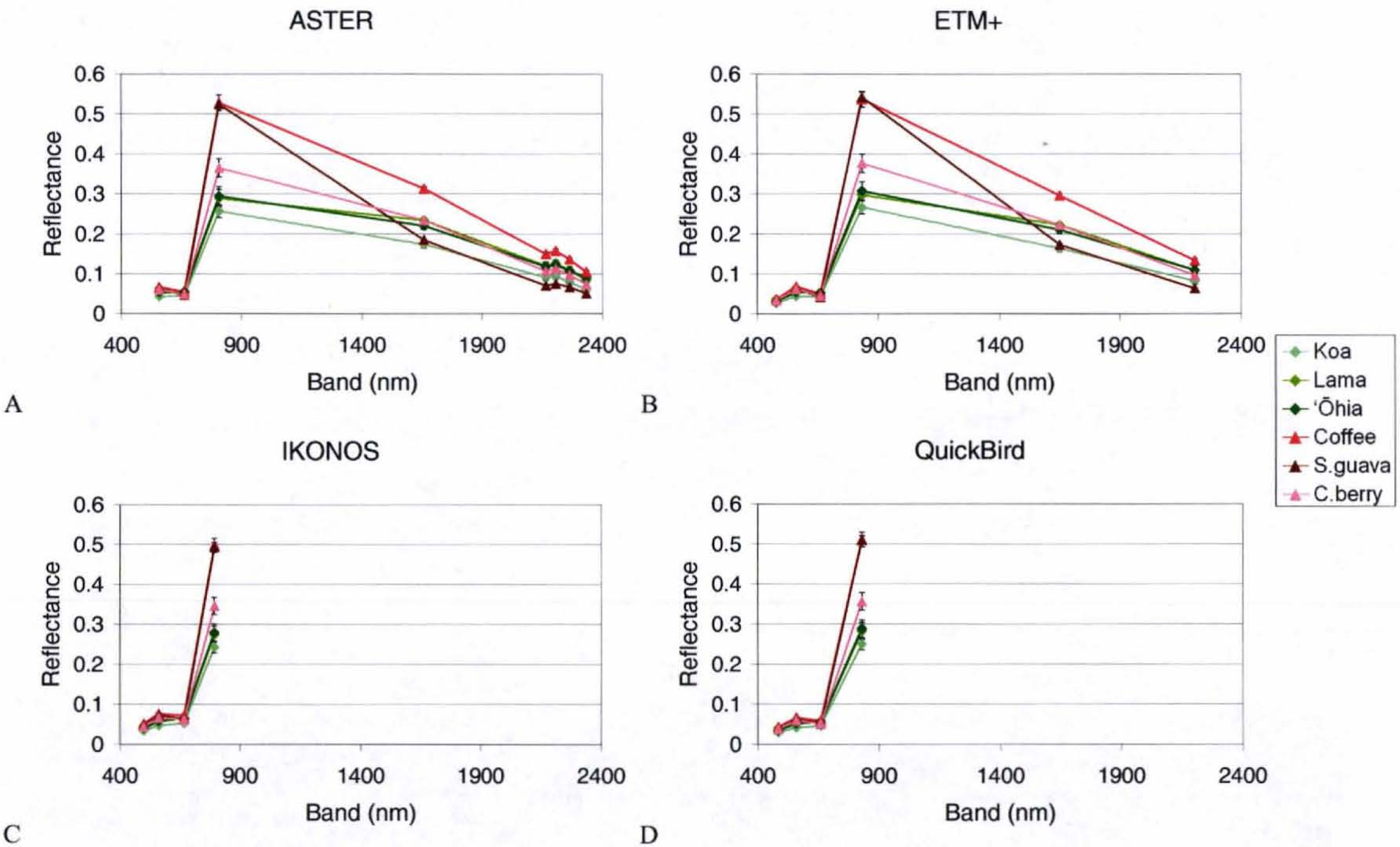

Figure 19. Mean Multispectral Canopy Reflectance

APPENDEX RESULTS OF T-TEST

A1. Result of *t*-test for PAI

α (significant level) = 0.002.

** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative).

Species	Koa*	Lama*	'Ōhia*	Coffee*	S.guava*	C.berry*
Koa		0.0082	0.0000	0.0000	0.0000	0.0000
Lama	0.0082		0.0419	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.0419		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.3359	0.0000
S.guava	0.0000	0.0000	0.0000	0.3359		0.0136
C.berry	0.0000	0.0000	0.0000	0.0000	0.0136	

A2. Result of *t*-test for LAD

α (significant level) = 0.002.

** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative).

Species	Koa**	Lama**	'Ōhia**	Coffee*	S.guava*	C.berry*
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0948	0.2161
S.guava	0.0000	0.0000	0.0000	0.0948		0.6774
C.berry	0.0000	0.0000	0.0000	0.2161	0.6774	

A3. Result of *t*-test for NPVAD

α (significant level) = 0.002.

** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative).

Species	Koa	Lama	'Ōhia	Coffee	S.guava*	C.berry*
Koa		0.0069	0.0068	0.4013	0.0000	0.0000
Lama	0.0069		0.0000	0.0852	0.0000	0.0000
'Ōhia	0.0068	0.0000		0.0000	0.0000	0.0000
Coffee	0.4013	0.0852	0.0000		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0126
C.berry	0.0000	0.0000	0.0000	0.0000	0.0126	

A4. Result of *t*-test for leaf reflectance with ASTER bands

α (significant level) = 0.002.

** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative).

(a) ASTER Green band (556.3 nm)

Species	Koa**	Lama**	'Ōhia	Coffee	S.guava*	C.berry*
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.0000		0.9291	0.0000	0.0000
Coffee	0.0000	0.0000	0.9291		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0046
C.berry	0.0000	0.0000	0.0000	0.0000	0.0046	

(b) ASTER Red band (661.0 nm)

Species	Koa**	Lama**	'Ōhia	Coffee	S.guava*	C.berry*
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.0000		0.7189	0.0000	0.0000
Coffee	0.0000	0.0000	0.7189		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0112
C.berry	0.0000	0.0000	0.0000	0.0000	0.0112	

(c) ASTER NIR band (806.8 nm)

Species	Koa*	Lama	'Ōhia*	Coffee	S.guava**	C.berry
Koa		0.0000	0.9273	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.3171	0.0000	0.0064
'Ōhia	0.9273	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.3171	0.0000		0.0000	0.0148
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0000	0.0064	0.0000	0.0148	0.0000	

(d) ASTER SWIR 1 band (1655.3 nm)

Species	Koa*	Lama	'Ōhia*	Coffee**	S.guava	C.berry
Koa		0.0000	0.0179	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.0351	0.5705
'Ōhia	0.0179	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0351	0.0000	0.0000		0.0208
C.berry	0.0000	0.5705	0.0000	0.0000	0.0208	

(e) ASTER SWIR 2-1 band (2167.0 nm)

Species	Koa*	Lama	'Ōhia*	Coffee**	S.guava	C.berry
Koa		0.0000	0.0420	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.0484	0.0874
'Ōhia	0.0420	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0484	0.0000	0.0000		0.0000
C.berry	0.0000	0.0874	0.0000	0.0000	0.0000	

(f) ASTER SWIR 2-2 band (2208.3 nm)

Species	Koa*	Lama	'Ōhia*	Coffee**	S.guava	C.berry
Koa		0.0000	0.0415	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.0275	0.3220
'Ōhia	0.0415	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0275	0.0000	0.0000		0.0000
C.berry	0.0000	0.3220	0.0000	0.0000	0.0000	

A4. (Continued) Result of *t*-test for leaf reflectance with ASTER bands

α (significant level) = 0.002.

** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative).

(g) ASTER SWIR 2-3 band (2265.1 nm)

Species	Koa**	Lama	'Ohia**	Coffee**	S.guava	C.berry
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.5397	0.0595
'Ohia	0.0000	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.5397	0.0000	0.0000		0.0000
C.berry	0.0000	0.0595	0.0000	0.0000	0.0000	

(h) ASTER SWIR 2-4 band (233.8 nm)

Species	Koa*	Lama	'Ohia*	Coffee**	S.guava*	C.berry
Koa		0.0000	0.1036	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.0000	0.0042
'Ohia	0.1036	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.5933
C.berry	0.0000	0.0042	0.0000	0.0000	0.5933	

(i) ASTER SWIR 2-5 band (2396.8 nm)

Species	Koa*	Lama*	'Ohia*	Coffee**	S.guava*	C.berry*
Koa		0.0042	0.0035	0.0000	0.0000	0.0000
Lama	0.0042		0.0000	0.0000	0.0000	0.0000
'Ohia	0.0035	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0006	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.1396
C.berry	0.0000	0.0000	0.0000	0.0000	0.1396	

A5. Result of *t*-test for leaf reflectance with ETM+ bands

α (significant level) = 0.002.

** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative).

(a) ETM+ Blue band (478.7 nm)

Species	Koa	Lama**	'Ōhia *	Coffee	S.guava*	C.berry*
Koa		0.0000	0.6057	0.0050	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.0000	0.0000
'Ōhia	0.6057	0.0000		0.0000	0.0000	0.0000
Coffee	0.0050	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0944
C.berry	0.0000	0.0000	0.0000	0.0000	0.0944	

(b) ETM+ Green band (561.0 nm)

Species	Koa**	Lama**	'Ōhia	Coffee	S.guava*	C.berry*
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.0000		0.7644	0.0000	0.0000
Coffee	0.0000	0.0000	0.7644		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0073
C.berry	0.0000	0.0000	0.0000	0.0000	0.0073	

(c) ETM+ Red band (661.4 nm)

Species	Koa**	Lama**	'Ōhia	Coffee	S.guava*	C.berry*
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.0000		0.9975	0.0000	0.0000
Coffee	0.0000	0.0000	0.9975		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0248
C.berry	0.0000	0.0000	0.0000	0.0000	0.0248	

(d) ETM+ NIR band (834.6 nm)

Species	Koa*	Lama	'Ōhia*	Coffee	S.guava**	C.berry
Koa		0.0000	0.8223	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.1027	0.0000	0.0036
'Ōhia	0.8223	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.1027	0.0000		0.0000	0.0610
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0000	0.0036	0.0000	0.0610	0.0000	

(e) ETM+ SWIR 1 band (1679.8 nm)

Species	Koa*	Lama	'Ōhia*	Coffee**	S.guava	C.berry
Koa		0.0000	0.0093	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.0254	0.8958
'Ōhia	0.0093	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0254	0.0000	0.0000		0.0000
C.berry	0.0000	0.8958	0.0000	0.0000	0.0000	

(f) ETM+ SWIR 2 band (2208.5 nm)

Species	Koa*	Lama	'Ōhia*	Coffee**	S.guava	C.berry
Koa		0.0000	0.0044	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.3199	0.0846
'Ōhia	0.0044	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.3199	0.0000	0.0000		0.0000
C.berry	0.0000	0.0846	0.0000	0.0000	0.0000	

A6. Result of *t*-test for leaf reflectance with IKONOS bands

α (significant level) = 0.002.

** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative).

(a) IKONOS Blue band (496.4 nm)

Species	Koa*	Lama**	'Ōhia*	Coffee**	S.guava*	C.berry*
Koa		0.0000	0.1743	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.0000	0.0000
'Ōhia	0.1743	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0022
C.berry	0.0000	0.0000	0.0000	0.0000	0.0022	

(b) IKONOS Green band (559.5 nm)

Species	Koa**	Lama**	'Ōhia	Coffee	S.guava**	C.berry**
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.0000		0.7366	0.0000	0.0000
Coffee	0.0000	0.0000	0.7366		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

(c) IKONOS Red band (666.3 nm)

Species	Koa**	Lama**	'Ōhia	Coffee	S.guava**	C.berry**
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.0000		0.6836	0.0000	0.0000
Coffee	0.0000	0.0000	0.6836		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

(d) IKONOS NIR band (791.6 nm)

Species	Koa*	Lama	'Ōhia*	Coffee	S.guava**	C.berry
Koa		0.0000	0.7947	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.1914	0.0000	0.0056
'Ōhia	0.7947	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.1914	0.0000		0.0000	0.0316
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0000	0.0056	0.0000	0.0316	0.0000	

A7. Result of *t*-test for leaf reflectance with QuickBird bands

α (significant level) = 0.002.

** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative).

(a) QuickBird Blue band (485.0 nm)

Species	Koa*	Lama**	'Ohia *	Coffee**	S.guava*	C.berry*
Koa		0.0000	0.6096	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.0000	0.0000
'Ohia	0.6096	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0218
C.berry	0.0000	0.0000	0.0000	0.0000	0.0218	

(b) QuickBird Green band (560.0 nm)

Species	Koa**	Lama**	'Ohia	Coffee	S.guava*	C.berry*
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.0000	0.0000
'Ohia	0.0000	0.0000		0.7396	0.0000	0.0000
Coffee	0.0000	0.0000	0.7396		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0023
C.berry	0.0000	0.0000	0.0000	0.0000	0.0023	

(c) QuickBird Red band (660.0 nm)

Species	Koa**	Lama**	'Ohia	Coffee	S.guava*	C.berry*
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.0000	0.0000
'Ohia	0.0000	0.0000		0.6308	0.0000	0.0000
Coffee	0.0000	0.0000	0.6308		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0027
C.berry	0.0000	0.0000	0.0000	0.0000	0.0027	

(d) QuickBird NIR band (830.0 nm)

Species	Koa*	Lama	'Ohia*	Coffee	S.guava**	C.berry
Koa		0.0000	0.7962	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.1705	0.0000	0.0049
'Ohia	0.7962	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.1705	0.0000		0.0000	0.0347
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0000	0.0049	0.0000	0.0347	0.0000	

A8. Result of *t*-test for leaf reflectance with NDVI

α (significant level) = 0.002.

** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative).

(a) ASTER NDVI

Species	Koa**	Lama**	'Ōhia	Coffee**	S.guava	C.berry**
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.0000		0.0000	0.3775	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0000	0.3775	0.0000		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

(b) ETM+ NDVI

Species	Koa	Lama**	'Ōhia	Coffee	S.guava	C.berry**
Koa		0.0000	0.0000	0.0024	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.0000		0.0000	0.4573	0.0000
Coffee	0.0024	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0000	0.4573	0.0000		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

(c) IKONOS NDVI

Species	Koa**	Lama**	'Ōhia	Coffee**	S.guava	C.berry**
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.0000		0.0000	0.1545	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0000	0.1545	0.0000		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

(d) QuickBird NDVI

Species	Koa**	Lama**	'Ōhia	Coffee**	S.guava	C.berry**
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.0000		0.0000	0.5607	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0000	0.5607	0.0000		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

A9. Result of *t*-test for leaf transmittance with ASTER bands

α (significant level) = 0.002.

** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative).

(a) ASTER Green band (556.3 nm)

Species	Koa**	Lama	'Ōhia**	Coffee	S.guava**	C.berry
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.1842	0.0000	0.0275
'Ōhia	0.0000	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.1842	0.0000		0.0000	0.2904
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0000	0.0275	0.0000	0.2904	0.0000	

(b) ASTER Red band (661.0 nm)

Species	Koa	Lama**	'Ōhia**	Coffee	S.guava**	C.berry
Koa		0.0000	0.0000	0.5603	0.0000	0.0591
Lama	0.0000		0.0000	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.0000		0.0000	0.0000	0.0000
Coffee	0.5603	0.0000	0.0000		0.0000	0.0189
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0591	0.0000	0.0000	0.0189	0.0000	

(c) ASTER NIR band (808.8 nm)

Species	Koa**	Lama	'Ōhia	Coffee	S.guava	C.berry**
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.6423	0.0000
'Ōhia	0.0000	0.0000		0.6643	0.0000	0.0000
Coffee	0.0000	0.0000	0.6643		0.0000	0.0000
S.guava	0.0000	0.6423	0.0000	0.0000		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

(d) ASTER SWIR 1 band (1655.3 nm)

Species	Koa	Lama**	'Ōhia**	Coffee**	S.guava**	C.berry
Koa		0.0000	0.0000	0.0000	0.0000	0.9126
Lama	0.0000		0.0000	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.9126	0.0000	0.0000	0.0000	0.0000	

(e) ASTER SWIR 2-1 band (2167.0 nm)

Species	Koa**	Lama*	'Ōhia*	Coffee**	S.guava**	C.berry**
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.1957	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.1957		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

(f) ASTER SWIR 2-2 band (2208.3 nm)

Species	Koa**	Lama*	'Ōhia*	Coffee**	S.guava**	C.berry**
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.2738	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.2738		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

A9. (Continued) Result of *t*-test for leaf transmittance with ASTER bands
α (significant level) = 0.002.
** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative).

(g) ASTER SWIR 2-3 band (2265.1 nm)

Species	Koa*	Lama*	'Ōhia*	Coffee**	S.guava**	C.berry**
Koa		0.0000	0.0017	0.0000	0.0000	0.0000
Lama	0.0000		0.1890	0.0000	0.0000	0.0000
'Ōhia	0.0017	0.1890		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

(h) ASTER SWIR 2-4 band (2333.8 nm)

Species	Koa*	Lama*	'Ōhia*	Coffee**	S.guava**	C.berry**
Koa		0.0203	0.0356	0.0000	0.0000	0.0000
Lama	0.0203		0.5823	0.0000	0.0000	0.0000
'Ōhia	0.0356	0.5823		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

(i) ASTER SWIR 2-5 band (2396.8 nm)

Species	Koa*	Lama*	'Ōhia*	Coffee**	S.guava**	C.berry**
Koa		0.3923	0.7030	0.0000	0.0000	0.0000
Lama	0.3923		0.5370	0.0000	0.0000	0.0000
'Ōhia	0.7030	0.5370		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

A10. Result of t-test for leaf transmittance with ETM+ bands
α (significant level) = 0.002.
** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative).

(a) ETM+ Blue band (478.7 nm)

Species	Koa	Lama*	'Ōhia*	Coffee*	S.guava**	C.berry
Koa		0.0000	0.0000	0.0000	0.0000	0.0028
Lama	0.0000		0.1693	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.1693		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.4125
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0028	0.0000	0.0000	0.4125	0.0000	

(b) ETM+ Green band (561.0 nm)

Species	Koa**	Lama	'Ōhia**	Coffee	S.guava**	C.berry
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.2347	0.0000	0.0459
'Ōhia	0.0000	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.2347	0.0000		0.0000	0.3328
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0000	0.0459	0.0000	0.3328	0.0000	

(c) ETM+ Rerd band (661.4 nm)

Species	Koa	Lama**	'Ōhia**	Coffee	S.guava**	C.berry
Koa		0.0000	0.0000	0.0035	0.0000	0.4010
Lama	0.0000		0.0000	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.0000		0.0000	0.0000	0.0000
Coffee	0.0035	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.4010	0.0000	0.0000	0.0000	0.0000	

(d) ETM+ NIR band (834.6 nm)

Species	Koa**	Lama	'Ōhia	Coffee	S.guava	C.berry**
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.6033	0.0000
'Ōhia	0.0000	0.0000		0.7834	0.0000	0.0000
Coffee	0.0000	0.0000	0.7834		0.0000	0.0000
S.guava	0.0000	0.6033	0.0000	0.0000		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

(e) ETM+ SWIR 1 (1649.8 nm)

Species	Koa	Lama**	'Ōhia**	Coffee**	S.guava**	C.berry
Koa		0.0000	0.0000	0.0000	0.0000	0.4569
Lama	0.0000		0.0000	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.4569	0.0000	0.0000	0.0000	0.0000	

(f) ETM+ SWIR 2 (2208.5 nm)

Species	Koa**	Lama*	'Ōhia*	Coffee**	S.guava**	C.berry**
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.3784	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.3784		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

A11. Result of *t*-test for leaf transmittance with IKONOS bands
α (significant level) = 0.002.
** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative).

(a) IKONOS Blue band (496.4 nm)

Species	Koa	Lama*	'Ōhia*	Coffee	S.guava**	C.berry
Koa		0.0000	0.0000	0.7562	0.0000	0.0604
Lama	0.0000		0.0028	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.0028		0.0000	0.0000	0.0000
Coffee	0.7562	0.0000	0.0000		0.0000	0.1273
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0604	0.0000	0.0000	0.1273	0.0000	

(b)IKONOS Green band (559.5 nm)

Species	Koa**	Lama	'Ōhia**	Coffee	S.guava**	C.berry
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.3075	0.0000	0.0333
'Ōhia	0.0000	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.3075	0.0000		0.0000	0.1798
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0000	0.0333	0.0000	0.1798	0.0000	

(c) IKONOS Red band (666.3 nm)

Species	Koa	Lama**	'Ōhia**	Coffee	S.guava**	C.berry
Koa		0.0000	0.0000	0.9751	0.0000	0.5766
Lama	0.0000		0.0000	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.0000		0.0000	0.0000	0.0000
Coffee	0.9751	0.0000	0.0000		0.0000	0.5943
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.5766	0.0000	0.0000	0.5943	0.0000	

(d) IKONOS NIR band (791.6 nm)

Species	Koa**	Lama	'Ōhia	Coffee	S.guava	C.berry**
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.4440	0.0000
'Ōhia	0.0000	0.0000		0.9824	0.0000	0.0000
Coffee	0.0000	0.0000	0.9824		0.0000	0.0000
S.guava	0.0000	0.4440	0.0000	0.0000		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

A12. Result of t-test for leaf transmittance with QuickBird bands

α (significant level) = 0.002.

** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative).

(a) QuickBird Blue band (485.0 nm)

Species	Koa	Lama*	'Ōhia*	Coffee	S.guava**	C.berry
Koa		0.0000	0.0000	0.2056	0.0000	0.0463
Lama	0.0000		0.0213	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.0213		0.0000	0.0000	0.0000
Coffee	0.2056	0.0000	0.0000		0.0000	0.4399
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0463	0.0000	0.0000	0.4399	0.0000	

(b) QuickBird Green band (560.0 nm)

Species	Koa**	Lama	'Ōhia**	Coffee	S.guava**	C.berry
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.1260	0.0000	0.0123
'Ōhia	0.0000	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.1260	0.0000		0.0000	0.2237
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0000	0.0123	0.0000	0.2237	0.0000	

(c) QuikcBird Red band (660.0 nm)

Species	Koa	Lama**	'Ōhia**	Coffee	S.guava**	C.berry
Koa		0.0000	0.0000	0.5845	0.0000	0.1437
Lama	0.0000		0.0000	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.0000		0.0000	0.0000	0.0000
Coffee	0.5845	0.0000	0.0000		0.0000	0.0602
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.1437	0.0000	0.0000	0.0602	0.0000	

(d) QuickBird NIR band (830.0 nm)

Species	Koa**	Lama	'Ōhia	Coffee	S.guava	C.berry**
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.4786	0.0000
'Ōhia	0.0000	0.0000		0.9442	0.0000	0.0000
Coffee	0.0000	0.0000	0.9442		0.0000	0.0000
S.guava	0.0000	0.4786	0.0000	0.0000		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

A13. Result of *t*-test for canopy reflectance with ASTER bands

α (significant level) = 0.002.

** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative).

(a) ASTER Green band (556.3 nm)

Species	Koa**	Lama	'Ohia**	Coffee	S.guava	C.berry
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0094	0.6617	0.4225
'Ohia	0.0000	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.0094	0.0000		0.0027	0.0619
S.guava	0.0000	0.6617	0.0000	0.0027		0.5589
C.berry	0.0000	0.4225	0.0000	0.0619	0.5589	

(b) ASTER Red band (661.0 nm)

Species	Koa	Lama	'Ohia**	Coffee	S.guava	C.berry
Koa		0.0662	0.0000	0.0506	0.7314	0.2139
Lama	0.0662		0.0000	0.6179	0.0000	0.1399
'Ohia	0.0000	0.0000		0.0100	0.0000	0.0000
Coffee	0.0506	0.6179	0.0100		0.0000	0.1260
S.guava	0.7314	0.0000	0.0000	0.0000		0.0080
C.berry	0.2139	0.1399	0.0000	0.1260	0.0080	

(c) ASTER NIR band (806.8 nm)

Species	Koa*	Lama*	'Ohia*	Coffee*	S.guava*	C.berry**
Koa		0.8233	0.5868	0.0000	0.0000	0.0000
Lama	0.8233		0.7713	0.0000	0.0000	0.0000
'Ohia	0.5868	0.7713		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.1543	0.0000
S.guava	0.0000	0.0000	0.0000	0.1543		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

(d) ASTER SWIR 1 band (1655.3 nm)

Species	Koa	Lama	'Ohia	Coffee**	S.guava	C.berry
Koa		0.0000	0.0000	0.0000	0.0077	0.0000
Lama	0.0000		0.5224	0.0000	0.0000	0.8458
'Ohia	0.0000	0.5224		0.0000	0.0000	0.6151
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0077	0.0000	0.0000	0.0000		0.0000
C.berry	0.0000	0.8458	0.6151	0.0000	0.0000	

(e) SWIR 2-1 band (2167.0 nm)

Species	Koa	Lama*	'Ohia	Coffee	S.guava**	C.berry
Koa		0.0000	0.0000	0.0000	0.0000	0.0025
Lama	0.0000		0.4954	0.0000	0.0000	0.0000
'Ohia	0.0000	0.4954		0.0024	0.0000	0.0000
Coffee	0.0000	0.0000	0.0024		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0025	0.0000	0.0000	0.0000	0.0000	

(f) SWIR 2-2 band (2208.3 nm)

Species	Koa**	Lama*	'Ohia*	Coffee**	S.guava**	C.berry**
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.7603	0.0000	0.0000	0.0000
'Ohia	0.0000	0.7603		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

A13. (Continued) Result of *t*-test for canopy reflectance with ASTER bands
α (significant level) = 0.002.
** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative).

(g) SWIR 2-3 band (2265.1 nm)

Species	Koa	Lama*	'Ōhia	Coffee	S.guava	C.berry**
Koa		0.0000	0.0000	0.0000	0.0167	0.0000
Lama	0.0000		0.3637	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.3637		0.0036	0.0000	0.0000
Coffee	0.0000	0.0000	0.0036		0.0000	0.0000
S.guava	0.0167	0.0000	0.0000	0.0000		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

(h) SWIR 2-4 band (2333.8 nm)

Species	Koa	Lama*	'Ōhia	Coffee	S.guava	C.berry
Koa		0.0000	0.0000	0.0000	0.0199	0.0022
Lama	0.0000		0.0365	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.0365		0.7743	0.0000	0.0000
Coffee	0.0000	0.0000	0.7743		0.0000	0.0000
S.guava	0.0199	0.0000	0.0000	0.0000		0.0000
C.berry	0.0022	0.0000	0.0000	0.0000	0.0000	

(i) SWIR 2-5 band (2396.8 nm)

Species	Koa	Lama	'Ōhia	Coffee	S.guava	C.berry
Koa		0.0000	0.0000	0.0000	0.0348	0.0115
Lama	0.0000		0.0238	0.0618	0.0000	0.0000
'Ōhia	0.0000	0.0238		0.2838	0.0000	0.0000
Coffee	0.0000	0.0618	0.2838		0.0000	0.0000
S.guava	0.0348	0.0000	0.0000	0.0000		0.0000
C.berry	0.0115	0.0000	0.0000	0.0000	0.0000	

A14. Result of *t*-test for canopy reflectance with ETM+ bands
α (significant level) = 0.002.
** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative).

(a) ETM+ Blue band (478.7 nm)

Species	Koa	Lama	'Ōhia	Coffee	S.guava	C.berry
Koa		0.0000	0.0298	0.0000	0.0051	0.0000
Lama	0.0000		0.0147	0.7802	0.0000	0.2236
'Ōhia	0.0298	0.0147		0.0109	0.7265	0.1538
Coffee	0.0000	0.7802	0.0109		0.0000	0.1657
S.guava	0.0051	0.0000	0.7265	0.0000		0.0579
C.berry	0.0000	0.2236	0.1538	0.1657	0.0579	

(b) ETM+ Green band (561.0 nm)

Species	Koa**	Lama	'Ōhia**	Coffee	S.guava	C.berry
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0088	0.6121	0.3596
'Ōhia	0.0000	0.0000		0.0000	0.0000	0.0000
Coffee	0.0000	0.0088	0.0000		0.0031	0.0751
S.guava	0.0000	0.6121	0.0000	0.0031		0.5082
C.berry	0.0000	0.3596	0.0000	0.0751	0.5082	

(c) ETM+ Red band (661.4 nm)

Species	Koa	Lama	'Ōhia**	Coffee	S.guava	C.berry
Koa		0.1523	0.0000	0.1953	0.6377	0.5382
Lama	0.1523		0.0000	0.9125	0.0000	0.0407
'Ōhia	0.0000	0.0000		0.0000	0.0000	0.0000
Coffee	0.1953	0.9125	0.0000		0.0000	0.1658
S.guava	0.6377	0.0000	0.0000	0.0000		0.0025
C.berry	0.5382	0.0407	0.0000	0.1658	0.0025	

(d) ETM+ NIR band (834.6 nm)

Species	Koa*	Lama*	'Ōhia*	Coffee*	S.guava*	C.berry**
Koa		0.9275	0.4262	0.0000	0.0000	0.0000
Lama	0.9275		0.5009	0.0000	0.0000	0.0000
'Ōhia	0.4262	0.5009		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.4587	0.0000
S.guava	0.0000	0.0000	0.0000	0.4587		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

(e) ETM+ SWIR 1 band (1649 nm)

Species	Koa	Lama	'Ōhia	Coffee**	S.guava	C.berry
Koa		0.0000	0.0000	0.0000	0.0195	0.0000
Lama	0.0000		0.7283	0.0000	0.0000	0.7016
'Ōhia	0.0000	0.7283		0.0000	0.0000	0.9557
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0195	0.0000	0.0000	0.0000		0.0000
C.berry	0.0000	0.7016	0.9557	0.0000	0.0000	

(f) ETM+ SWIR 2 band (2208.5 nm)

Species	Koa**	Lama*	'Ōhia	Coffee	S.guava**	C.berry**
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.3261	0.0000	0.0000	0.0000
'Ōhia	0.0000	0.3261		0.0409	0.0000	0.0000
Coffee	0.0000	0.0000	0.0409		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

A15. Result of *t*-test for canopy reflectance with IKONOS bands
α (significant level) = 0.002.
** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative).

(a) IKONOS Blue band (496.4 nm)

Species	Koa*	Lama	'Ōhia	Coffee**	S.guava*	C.berry
Koa		0.0000	0.0089	0.0000	0.0000	0.0000
Lama	0.0000		0.0403	0.0000	0.0000	0.1366
'Ōhia	0.0089	0.0403		0.0000	0.0000	0.0028
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.1657
C.berry	0.0000	0.1366	0.0028	0.0000	0.1657	

(b) IKONOS Green band (559.5 nm)

Species	Koa**	Lama	'Ōhia*	Coffee**	S.guava*	C.berry
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0045	0.0000	0.0000	0.0458
'Ōhia	0.0000	0.0045		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0000
S.guava	0.0000	0.0000	0.0000	0.0000		0.1516
C.berry	0.0000	0.0458	0.0000	0.0000	0.1516	

(c) IKONOS Red band (666.3 nm)

Species	Koa	Lama	'Ōhia	Coffee	S.guava	C.berry
Koa		0.0264	0.0000	0.0000	0.0020	0.0039
Lama	0.0264		0.0000	0.0000	0.0072	0.0800
'Ōhia	0.0000	0.0000		0.5801	0.0260	0.0266
Coffee	0.0000	0.0000	0.5801		0.0000	0.0000
S.guava	0.0020	0.0072	0.0260	0.0000		0.7546
C.berry	0.0039	0.0800	0.0266	0.0000	0.7546	

(d) IKONOS NIR band (791.6 nm)

Species	Koa*	Lama*	'Ōhia*	Coffee*	S.guava*	C.berry**
Koa		0.7402	0.5123	0.0000	0.0000	0.0000
Lama	0.7402		0.7765	0.0000	0.0000	0.0000
'Ōhia	0.5123	0.7765		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.1281	0.0000
S.guava	0.0000	0.0000	0.0000	0.1281		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

A16. Result of *t*-test for canopy reflectance with QuickBird bands
α (significant level) = 0.002.
** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative).

(a) QuickBird Blue band (485.0 nm)

Species	Koa*	Lama	'Ōhia	Coffee*	S.guava	C.berry
Koa		0.0000	0.0166	0.0000	0.0000	0.0000
Lama	0.0000		0.0214	0.0000	0.8404	0.8634
'Ōhia	0.0166	0.0214		0.0000	0.0176	0.0249
Coffee	0.0000	0.0000	0.0000		0.0000	0.0048
S.guava	0.0000	0.8404	0.0176	0.0000		0.7244
C.berry	0.0000	0.8634	0.0249	0.0048	0.7244	

(b) QuickBird Green band (560.0 nm)

Species	Koa**	Lama	'Ōhia **	Coffee*	S.guava	C.berry
Koa		0.0000	0.0000	0.0000	0.0000	0.0000
Lama	0.0000		0.0000	0.0000	0.1185	0.2446
'Ōhia	0.0000	0.0018		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0000	0.0096
S.guava	0.0000	0.1185	0.0000	0.0000		0.9041
C.berry	0.0000	0.2446	0.0000	0.0096	0.9041	

(c) QuickBird Red band (660.0 nm)

Species	Koa	Lama	'Ōhia	Coffee	S.guava	C.berry
Koa		0.0409	0.0000	0.0043	0.1731	0.0742
Lama	0.0409		0.0066	0.0386	0.0098	0.5606
'Ōhia	0.0000	0.0066		0.1809	0.0000	0.0036
Coffee	0.0043	0.0386	0.1809		0.0000	0.0190
S.guava	0.1731	0.0098	0.0000	0.0000		0.1521
C.berry	0.0742	0.5606	0.0036	0.0190	0.1521	

(d) QuickBird NIR band (830.0 nm)

Species	Koa*	Lama*	'Ōhia *	Coffee*	S.guava*	C.berry**
Koa		0.7956	0.4909	0.0000	0.0000	0.0000
Lama	0.7956		0.6954	0.0000	0.0000	0.0000
'Ōhia	0.4909	0.6954		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.1863	0.0000
S.guava	0.0000	0.0000	0.0000	0.1863		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

A17. **Result of *t*-test for canopy reflectance with NDVI**
α (significant level) = 0.002.
**** indicates significantly different from all the other species, * indicates significantly different from the other group of species (native or nonnative).**

(a) ASTER NDVI

Species	Koa	Lama*	'Ōhia*	Coffee*	S.guava*	C.berry
Koa		0.1354	0.0091	0.0000	0.0000	0.0035
Lama	0.1354		0.0740	0.0000	0.0000	0.0000
'Ōhia	0.0091	0.0740		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0245	0.0000
S.guava	0.0000	0.0000	0.0000	0.0245		0.0000
C.berry	0.0035	0.0000	0.0000	0.0000	0.0000	

(b) ETM+ NDVI

Species	Koa*	Lama*	'Ōhia*	Coffee*	S.guava*	C.berry**
Koa		0.1883	0.0149	0.0000	0.0000	0.0000
Lama	0.1883		0.0806	0.0000	0.0000	0.0000
'Ōhia	0.0149	0.0806		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0047	0.0000
S.guava	0.0000	0.0000	0.0000	0.0047		0.0000
C.berry	0.0000	0.0000	0.0000	0.0000	0.0000	

(c) IKONOS NDVI

Species	Koa	Lama*	'Ōhia*	Coffee*	S.guava*	C.berry
Acakoa		0.0905	0.0056	0.0000	0.0000	0.0083
Koa	0.0905		0.0744	0.0000	0.0000	0.0000
Lama	0.0056	0.0744		0.0000	0.0000	0.0000
'Ōhia	0.0000	0.0000	0.0000		0.0227	0.0000
Coffee	0.0000	0.0000	0.0000	0.0227		0.0000
S.guava	0.0083	0.0000	0.0000	0.0000	0.0000	

(d) QuickBird NDVI

Species	Koa	Lama*	'Ōhia*	Coffee*	S.guava*	C.berry
Koa		0.0979	0.0136	0.0000	0.0000	0.0043
Lama	0.0979		0.1583	0.0000	0.0000	0.0000
'Ōhia	0.0136	0.1583		0.0000	0.0000	0.0000
Coffee	0.0000	0.0000	0.0000		0.0275	0.0000
S.guava	0.0000	0.0000	0.0000	0.0275		0.0000
C.berry	0.0043	0.0000	0.0000	0.0000	0.0000	

LITERATURE CITED

Asner, G. P. 1998. Biophysical and biochemical sources of variability in canopy reflectance. *Remote Sensing of Environment* 64: 234-253.

Asner, G. P. and Vitousek, P. M. 2005. Remote analysis of biological invasion and biogeochemical change. *PNAS* 102 (12): 4383-4386.

Baranoski, G. V. G. and Rokne, J. G. 2004. Light interaction with plants: a computer graphics perspective. Horwood Publishing, Chichester, England.

Barros, R. S., Da S.e Mota, J. W., Da Matta, F., Maestri, M. 1997. Decline of vegetative growth in *Coffea arabica* L. in relation to leaf temperature, water potential and stomatal conductance. *Field Crops Research* 54: 65-72.

Big Island Invasive Species Committee 2003. Operation of Miconia. Available at: http://www.hear.org/operationmiconia/index.html

Campbell, G. S. 1990. Derivation of an angle density function for canopies with ellipsoidal leaf angle distributions. *Agricultural and Forest Meteorology* 49: 173-176.

Chen, J. M. and Cihlar, J. 1995. Plant canopy gap size analysis theory for improving optical measurements of leaf area index. *Applied Optics* 34 (27): 6211-6222.

Chen, J. M. Optically-based methods for measuring seasonal variation of leaf area index in boreal conifer stands. 1996. *Agricultural and Forest Meteorology* 80: 135-163.

Clark, M. L., Roberts, D. A. and Clark, D. B. 2005. Hyperspectral discrimination of tropical rainforest tree species at leaf to crown scales. *Remote Sensing of Environment* 96: 375-398.

Daughtry, C. S. T., L. L. Biehl, and K. J. Ranson. 1989. A new technique to measure the spectral properties of conifer needles. *Remote Sensing of Environment* 27: 81-91.

Dymond, J. R. and Shepherd, J. D. 2004. The spatial distribution of indigenous forest and its composition in the Wellington region, New Zealand, from ETM+ satellite imagery. *Remote Sensing of Environment* 90: 116-125.

Ewel, J. J., Ojima, D. S., Karl, D. A. and DeBusk, W. F. 1982. Schinus in successional ecosystems of Everglades National Park. Tech. Rep. T-676, Natl. Park Serv. So. Fla. Res. Cent., Everglades Natl. Park. Homestead, Fla.

Foody, G. M. 2002. Status of land cover classification accuracy assessment. *Remote Sensing of Environment* 80: 185-201.

Gamon, J. A., Field, C. B. Goulden, M. L. Griffin, K. L., Hartley, A. E., Joel, G., Peñuelas, J. and Valentini, R. 1995. Relationships between NDVI, canopy structure, and photosynthesis in three Californian vegetation types. *Ecological Applications* 5 (1): 28-41.

Gates, D. M., Keegan, H. J., Schleter, J. C. and Weidner, V. R. 1965. Spectral properties of plants. *Applied Optics* 4 (1): 11-20.

Giambelluca, T. W., Nullet, M. A., and Schroeder, T. A. 1986. Hawaii Rainfall Atlas, Report R76, Hawaii Division of Water and Land Development, Department of Land and Natural Resources, Honolulu. vi + 267 p.

Goel, N. S. and Thompson, R. L. 2000. A snapshot of canopy reflectance models and a universal model for the radiation regime. *Remote Sensing Reviews* 18: 197-225.

Hessburg, P. F., Smith, B. G., Salter, R. B., Ottmar, R. D. & Alvarado, E. 2000. Recent changes (1930s-1990s) in spatial patterns of interior northwest forests, USA. *Forest Ecology and Mangement* 136: 53-83.

Hobbs, R. J. & Humphries, S. E. 1994. An integrated approach to the ecology and management of plant invasions. *Conservation Biology* 9 (4): 761-770.

Joshi, C., de Leeuw, J. and van Duren I.C. 2004. Remote sensing and GIS applications for mapping and spatial modeling of invasive species. *XXth International Society for Photogrammetry and Remote Sensing Congress*, 12-23 July 2004, Istanbul, Turkey.

Kucharik, C. J., Norman, J. M. and Gower, S. T. 1998. Measurements branch area and adjusting leaf area index indirect measurements. *Agricultural and Forest Meteorology* 91: 69-88.

LI-COR Inc. 1992. LAI-2000 plant canopy analyzer operating manual.

LaRosa, A. M., Doren, R. F. and Gunderson, L. 1992. Alien Plant Management in Everglades National Park: Historical Perspective. Pages 47-63 *in* Stone, C. P., Smith, C. W. and Tunison, J. T. (eds.) Alien plant invasions in native ecosystems of Hawaii: management and research. University of Hawaii Cooperative National Park Resources Studies Unit, Honolulu.

Lass, L. W. and Prather, T. S. 2004. Detecting the locations of Brazilian pepper trees in Everglades with a hyperspectral sensor. *Weed Technology* 18: 437-442.

Lass, L. W., Prather, T. S., Glenn, N. F., Weber, K. T., Mundt, J. T. & 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.

Loope, L. L. 1992. An overview of problems with introduced plant species in national parks and biosphere reserves of the United States. Pages 3-28 *in* Stone, C. P., Smith, C. W. and Tunison, J. T. (eds.) Alien plant invasions in native ecosystems of Hawaii: management and research. University of Hawaii Cooperative National Park Resources Studies Unit, Honolulu.

Loope, L. L. 1999. Hawaii and the Pacific Islands. Pages 747-774 *in* Mac, M. J., Opler, P. A., Puckett Haecker, C. E. and Dorans, P. D. (eds) Status and trends of the nation's biological resources. Volume 2. Reston, VA: U.S. Department of the Interior, U.S. Geological Survey Biological Resources Division. www.hear.org/AlienSpeciesInHawaii/articles/hawaii_and_Pacific.pdf

Mack, R. N. 2005. Assessing biotic invasions in time and space: the second imperative. Pages 179-208 *in* H. A. Mooney, Mack, R. N., McNeely, J. A., Neville, L. E., Schei P. J. & Waage, J. K. Invasive alien species: a new synthesis. Island Press, Washington, DC.

Medeiros, A. C., Loope, L. L., Conant, P. and McElvaney, S. 1997 Status, ecology, and management of the invasive plant, *Miconia calvescens* DC (Melastomataceae) in the Hawaiian Islands. *Bishop Museum Occasional Papers* 48: 23-36.

Meyer, J-Y. and Florence, J. 1996. Tahiti's native flora endangered by the invasion of Miconia calvescens DC. (Melastomataceae). *J. of Biogeography* 23 (6): 775-781.

Miller, J. B. 1967. A formula for average foliage density. *Australian Journal of Botany* 15: 141-144.

Miller, R.G. Jr. 1981. Simultaneous statistical inference. Springer-Verlag, NewYork, U.S.

Myneni, R. B., Maggion, S., Iaquinta, J., Privetta, J. L., Gobron, N., Pinty, B., Kimes, D. S., Verstraeta, M. M. and Williams, D. L. 1995. Optical remote sensing of vegetation: modeling, caveats, and algorithms. *Remote Sensing of Environment* 51: 169-188.

National Invasive Species Council. 2001. Meeting the Invasive Species Challenge: The National Invasive Species Management Plan, Washington DC, 88 pages.

Powell, R. L., Matzke, N., de Souza Jr., C., Clark, M., Numata, I., Hess, L. L. & Roberts, D. A. 2004. Sources of error in accuracy assessment of thematic land-cover maps in the Brazilian Amazon. *Remote Sensing of Environment* 90: 221-234.

Rew, L. J., Maxwell, B. D. & Aspinall, R. 2005. Predicting the occurrence of nonindigenous species using environmental and remotely sensed data. *Weed Science* 53: 236-241.

Richards, J. A. and Jia, X. 1999. Remote sensing digital image analysis: an introduction. Springler-Verlag Berlin, Germany.

Roberts, D. A., Nelson, B. W., Adams, J. B. and Palmer, F. 1998. Spectral changes with leaf aging in Amazon caatinga. *Trees* 12: 315-325.

Roberts, D. A., Ustin, S. L., Ogunjemiyo, S., Greenberg, J. Dobrowski, S. Z., Chen, J. and Hinckley, T. M. 2004. Spectral and structural measures of Northwest forest vegetation at leaf to landscape scales. *Ecosystems* 7: 545-562.

Sánchez-Azofeifa, G. A., Castro, K. L. & Kalascka, M. R. 2003. Remote sensing research priorities in tropical dry forest environments. *BIOTROPICA* 35 (2): 134-142

Schnase, J. L., Smith, J.A., Stohlgren, T. J., Graves, S. and Trees, C. 2002. Biological invasions: a challenge in ecological forecasting. Pages 122-124 *in* Geoscience and Remote Sensing Symposium, 2002. IGARSS '02. 2002 IEEE International.

Schott, J. R. 1997. Remote sensing: The image chain approach. Oxford University Press, New York.

Schowengerdt, R. A. 1997. Remote Sensing, Models and Methods for Image Processing. Elsevier Science, California.

Smith, W. C. 1985. Impacts of alien plants on Hawai'i's native biota. Pages 180-280 *in* Stone, C. P and Scott, J. M. (eds.) Hawai'i's terrestrial ecosystems; preservation and management. University of Hawai'i Cooperative National Park Resources Studies Unit, Honolulu.

Staples, G. W. and Herbst, D. R. 2005. A Tropical Garden Flora. Bishop Museum, Honolulu, Hawai'i.

The Canada Center for Remote Sensing (CCRS). 2005. Fundamentals of Remote Sensing. Natural Resources Canada. Available at: http://ccrs.nrcan.gc.ca/resource/tutor/fundam/pdf/fundamentals_e.pdf

The Hawai'i Gap Project: Assessing Biodiversity Management. 2005. Available at: http://www.higap.org/

Tucker, C. J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment* 8: 127-150.

Turner, W., Spector, S., Gardiner, N., Fladeland, M., Sterling, E. and Steininger, M. 2003. Remote sensing for biodiversity science and conservation. *TRENDS in Ecol. and Evol.* 18 (6): 306-314.

United States Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS). Soil Survey of the State of Hawai'i. Available at:

http://www.ctahr.hawaii.edu/soilsurvey/soils.htm

U. S. Congress, Office of Technology Assessment (OTA). 1993. Harmful non-indigenous species in the United States. OTA-F-565. U. S. Government Printing Office, Washington, DC.

Wagner, W.L., Herbst, D.R. and Sohmer, S.H. 1999. Manual of the flowering plants of Hawai'i. Revised edition. University of Hawai'i Press, Honolulu.

Wagner, W. L., D. R. Herbst, and D. H. Lorence. 2005-. Flora of the Hawaiian Islands website.
http://ravenel.si.edu/botany/pacificislandbiodiversity/hawaiianflora/index.htm

Wester, L. 1992. Origin and distribution adventive alien flowering plants. Pages 99-154 *in* Stone, C. P., Smith, C. W. and Tunison, J. T. (eds.) Alien plant invasions in native ecosystems of Hawaii: management and research. University of Hawaii Cooperative National Park Resources Studies Unit, Honolulu.

Verhoef, W. 1984. Light scattering by leaf layers with application to canopy reflectance modeling: The SAIL model. *Remote Sensing of Environment* 16: 125-141.

Wilcove D. S., Rothstein D., Dubow J., Phillips A. and Losos E. 1998. Quantifying threats to imperiled species in the United States. *BioScience* 48(8): 607-615.

Woolley, J. T. 1971. Reflectance and transmittance of light by leaves. *Plant Physiology* 47 (5): 656-662.