LEAF OPTICAL PROPERTIES

Plant leaves collectively represent the largest above-ground surface area of plant material in virtually all environments. Their optical properties determine where and how energy and gas exchange occurs, which in turn drives the energy budget of the planet, and defines its ecology and habitability. This book reviews the state-of-the-art research on leaf optics. Topics covered include leaf traits, the anatomy and structure of leaves, leaf color, biophysics and spectroscopy, radiometry, radiative transfer models, and remote and proximal sensing. A physical approach is emphasized throughout, providing the necessary foundations in physics, chemistry, and biology to make the context accessible to readers from various subject backgrounds. It is a valuable resource for advanced students, researchers, and government agency practitioners in remote sensing, plant physiology, ecology, resource management, and conservation.

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Preface

Plant leaves are the main surfaces of phyto-elements in most plant communities. They are all around us, but contrary to flowers, only a few books have focused on them: in their book *Leaves*, Prance and Sandved (1985) paint a fascinating picture of their formation, characteristics, and uses. Their book presents more than 300 breathtaking photos of leaves taken from their travels around the world. At the age of 87, Vitale (1997) released her first book, *Leaves: In Myth, Magic & Medicine*, based on research she conducted over almost 30 years. She provides authentic portraits of 110 leaf specimens all grown in North America, mixing delightful short stories of where they originate, how they inspired poets and myth-makers, or how they were used as medicines. Among the many subjects that these authors cover is leaf color, but only in passing. The interaction of light with plant leaves, which results in leaf color, is nevertheless of interest to the botanist, forester, geographer, biophysicist, biochemist, ecologist, hydrologist, agronomist, and others. Because leaves collectively represent the largest surface area of plant material in virtually all environments, they drive the energy budget of the planet and define its ecology and its habitability. It is worthwhile remembering that the photosynthetic function of leaves is essential for life on Earth (Vogelmann and Gorton, 2014).

Lee's *Nature's Palette: The Science of Plant Color* (Lee, 2007) is one of the first books entirely devoted to plant color, taking the reader through its social history, ecology, evolution, and biochemistry. It includes flowers, leaves, fruits and seeds, stems, and roots. His approach is, however, mainly that of a chemist or a biologist. The book *Photoprotection in Plants – Optical Screening-based Mechanisms* (Solovchenko, 2010) deals with the optical screening of excessive and potentially harmful solar radiation by plant leaves. Photoprotection is important for juvenile and senescing plants as well as when under environmental stresses. Visual plant defenses (camouflage, mimicry and aposematism via coloration, morphology, and even movement) against herbivores is the central topic of *Defensive (anti-herbivory) Coloration in Land Plants* (Lev-Yadun, 2016). That book develops the author's current understanding on defensive plant coloration and related issues.

Leaf optical properties have been the subject of hundreds of studies, most since the middle of the last century. Despite their obvious importance in many scientific domains including plant physiology, ecology, remote sensing, environmental physics, or image synthesis, a reference book that covers the entire subject of how light interacts with plant leaves has not previously been published. This book reviews the state-of-the-science of leaf optics. Because of the depth of this subject, we have restrained from adding sections on canopy and landscape-scale processes, because of the impractical length of such a book and because there are other books that address these subjects.

This book was written for the interested scientists who work across the wide range of disciplines cited above. Many of these readers do not share a common understanding of these properties, therefore we have included brief descriptions of the fundamental discoveries in leaf optics in the solar domain, thermal infrared, and microwaves and how these relate to other disciplines. The first four chapters provide descriptions of the basic component parts of plants and their relevant biochemical composition, then how light is absorbed or scattered by leaf constituents in different wavelength regions, and finally, how light interactions are measured. These are the building blocks that determine what materials light can interact with. All of these are presented in the context of how light interacts with biological and physical processes. Chapters 5 to 7 describe the optical properties of leaves and the sources of variability; these are the physical rules that control the interactions. Chapters 8 to 10 review leaf reflectance models, their uses and limitations, and provide a detailed review of the most widely used leaf optics model, PROSPECT, and a three-dimensional ray tracing model, RAYTRAN. Chapters 11 and 12 include information extraction methods and their application to a wide range of applications. A short conclusion is followed by references and then several appendices that provide more detail on several of the physical and optical processes, mathematical methods, and available datasets.

Symbols

A	absorptance
A	one-sided area of a fresh leaf (m^2)
c	velocity of light in a vacuum (2.998×10^8 m s^{-1})
C	capacitance of a medium
d_p	penetration depth of light (m)
dw	leaf dry mass (kg)
E	irradiance (W m^{-2})
$F_{\parallel}$	parallel component of the Fresnel equations
$F_{\perp}$	perpendicular component of the Fresnel equations
fw	leaf fresh mass (kg)
h	Planck's constant (6.626×10^{-34} J s)
I	radiant intensity (W sr^{-1})
I_c	upward collimated radiant flux
I_d	upward diffuse radiant flux
I_p	intensity of the polarized component of light
I_u	intensity of the unpolarized component of light
J_c	downward collimated radiant flux
J_d	downward diffuse radiant flux
k	specific absorption coefficient (m^{-1})
k_B	Boltzmann constant (1.38×10^{-23} J K^{-1})
ℓ	leaf thickness (m)
L	radiance (W m^{-2} sr^{-1})
L_e	spectral radiance of a blackbody (W $m^{-2}\mu m^{-1}$ sr^{-1})
M	radiant emittance (or radiant exitance) (W m^{-2})
$\tilde{n}$	complex refractive index, $\tilde{n} = n_r + i\, n_i$
n_r	real part of the complex refractive index (or refractive index noted n)
n_i	imaginary part of the complex refractive index
N_A	Avogadro number (6.02214×10^{23} mol^{-1})
p	degree of polarization of light
q	energy of a photon (J or eV)
Q	magnitude of the polarization ellipse
Q	radiant energy (J)
R	reflectance

R	resistance of a medium
r_{ij}	average reflectivity from medium *i* to medium *j*
s	scattering coefficient of a medium (m^{-1})
$\vec{S}$	Stokes vector
t_{ij}	average transmissivity from medium *i* to medium *j*
T	transmittance
T	absolute temperature (K)
U	orientation of the polarization ellipse
v	velocity of light in a medium ($m\ s^{-1}$)
V	circularity of the polarization ellipse
Γ	reflection coefficient in the microwaves
$\tilde{\epsilon}$	relative dielectric permittivity, $\tilde{\epsilon}_r = \epsilon_r + i\epsilon_i$
ϵ_0	vacuum permittivity ($8.854 \times 10^{-12}\ F\ m^{-1}$)
ϵ_{eff}	effective dielectric constant of a medium
ϵ_i	imaginary part of the relative dielectric permittivity (or loss factor noted ϵ'')
ϵ_r	real part of the relative dielectric permittivity (or dielectric constant noted ϵ')
θ_c	critical angle (° or rad)
θ_B	Brewster's angle (° or rad)
λ	wavelength (m)
ν	frequency (Hz)
ξ	polarization azimuth
ρ_d	leaf density (dry mass per unit volume) ($kg\ m^{-3}$)
σ	wavenumber (m^{-1})
σ_e	extinction coefficient of a medium (m^{-1})
σ_k	absorption coefficient of a medium (m^{-1})
σ_s	scattering coefficient of a medium (m^{-1})
τ	fraction of light transmitted through a medium
Φ	radiant flux (or radiant power) ($J\ s^{-1}$ or W)
χ	shape of the polarization ellipse
ψ	leaf water potential (Pa)
ω	angular frequency ($rad\ s^{-1}$)
Ω	solid angle (sr)

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