

Package ‘ccrtm’

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Type Package

Title Coupled Chain Radiative Transfer Models

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Description A set of radiative transfer models to quantitatively describe the absorption, reflectance and transmission of solar energy in vegetation, and model remotely sensed spectral signatures of vegetation at distinct spatial scales (leaf, canopy and stand). The main principle behind ccrtm is that many radiative transfer models can form a coupled chain, basically models that feed into each other in a linked chain (from leaf, to canopy, to stand, to atmosphere). It allows the simulation of spectral datasets in the solar spectrum (400-2500nm) using leaf models as PROSPECT5, 5b, and D which can be coupled with canopy models as 'FLIM', 'SAIL' and 'SAIL2'. Currently, only a simple atmospheric model ('skyl') is implemented. Jacquemoud et al 2008 provide the most comprehensive overview of these models <doi:10.1016/j.rse.2008.01.026>.

License GPL (>= 2)

URL <https://github.com/MarcoDVisser/ccrtm>

BugReports <https://github.com/MarcoDVisser/ccrtm/issues>

Imports graphics, grDevices, stats, testthat, Rcpp (>= 1.0.3), expint, pracma

LinkingTo Rcpp

Repository CRAN

RoxygenNote 7.0.2

NeedsCompilation yes

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bRTM	<i>Generates an invertable model for backward implementation of Radiative Transfer Models</i>
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Description

Generates an invertable model for backward implementation of Radiative Transfer Models

Usage

```
bRTM(fm = rho ~ prospect5, data = NULL, pars = NULL, fixed = NULL,
      wl = 400:2500)
```

Arguments

fm	A formula specifying which rtm to run
data	ignored as of yet

pars	a list of <code>_named_</code> parameter vectors for all models. The parameter list for a model call as <code>rho ~ prospect + foursail</code> therefore contains two named vectors the first with parameters for <code>prospect</code> and the second with parameters for <code>foursail</code> if left empty default parameters are generated
fixed	a list of parameters to fix
wl	wavelengths (in nm) add only if certain wavelengths are required as output. Input is expected to integers between 400 and 2500, or will be forced to be an integer. Integers outside the 400:2500 range will not be returned.

cambell	<i>Leaf inclination distribution function Ellipsoidal distribution function</i>
---------	---

Description

Leaf inclination distribution function Ellipsoidal distribution function

Usage

```
cambell(ala, tx1, tx2)
```

Arguments

ala	average leaf angle parameter
tx1	angle in degree
tx2	angle in degree

Value

angle fraction value

ccrtm	<i>ccrtm: Coupled Chain Radiative Transfer Models.</i>
-------	--

Description

A collection of radiative transfer models that can form a coupled chain to model radiative transfer across multiple spatial scales from leaf to canopy to stand.

Details

Currently implemented models:

- [1] = PROSPECT 5, 5B and D
- [2] = FOURSAIL, and FOURSAIL2
- [3] = FLIM

Currently being tested or to be implemented models

- [1] = LIBERTY, PROCOSINE
- [2] = INFORM

Author(s)

Marco D. Visser

cdcum

*Leaf inclination distribution function cummulative lagden function
from Wout Verhoef's dissertation Extended here for any angle*

Description

Leaf inclination distribution function cummulative lagden function from Wout Verhoef's dissertation Extended here for any angle

Usage

cdcum(a, b, theta)

Arguments

a	parameter
b	parameter
theta	angle in degrees

Value

angle fraction value

data_prospect5	<i>refractive index and specific absorption coefficient for PROSPECT 5</i>
----------------	--

Description

see <http://teledetection.ipgp.jussieu.fr/prosail/> for more details on the data.

Usage

```
data(prospect5)
```

details

```
***** data_prospect5  
(february, 25th 2008) The dataset contains the following labels (columns): *****
```

- [1] = wavelength (nm)
- [2] = refractive index of leaf material (or the ratio of the velocity of light in a vacuum to its velocity in "leaf medium").
- [3] = specific absorption coefficient of chlorophyll (a+b) (cm2.microg-1)
- [4] = specific absorption coefficient of carotenoids (cm2.microg-1)
- [5] = specific absorption coefficient of brown pigments (arbitrary units)
- [6] = specific absorption coefficient of water (cm-1)
- [7] = specific absorption coefficient of dry matter (g.cm-1)
- [8] = direct light
- [9] = diffuse light
- [10] = dry soil
- [11] = wet soil

references

Feret et al. (2008), PROSPECT-4 and 5: Advances in the Leaf Optical Properties Model Separating Photosynthetic Pigments, Remote Sensing of Environment

data_prospectd	<i>refractive index and specific absorption coefficient for PROSPECT D</i>
----------------	--

Description

see <http://teledetection.ipgp.jussieu.fr/prosail/> for more details on the data.

Usage

data(prospectd)

details

***** data_prospect5
 (february, 25th 2008) The dataset contains the following labels (columns): *****

- [1] = wavelength (nm)
- [2] = refractive index of leaf material (or the ratio of the velocity of light in a vacuum to its velocity in "leaf medium").
- [3] = specific absorption coefficient of chlorophyll (a+b) (cm2.microg-1)
- [4] = specific absorption coefficient of carotenoids (cm2.microg-1)
- [5] = specific absorption coefficient of brown pigments (arbitrary units)
- [6] = specific absorption coefficient of water (cm-1)
- [7] = specific absorption coefficient of dry matter (g.cm-1)
- [8] = direct light
- [9] = diffuse light
- [10] = dry soil
- [11] = wet soil

references

Feret et al. (2008), PROSPECT-4 and 5: Advances in the Leaf Optical Properties Model Separating Photosynthetic Pigments, Remote Sensing of Environment

flim *Forest Light Interaction Model (FLIM)*

Description

The FLIM model was first described by Rosema et al (1992). In FLIM forests are assumed a discontinuous mix of tree crowns and gaps. Reflectance is modelled in terms of the probability to observe either a gap (background) or a tree crown. Both gaps and crowns may be shaded.

Usage

```
flim(Rc, Rg, To = NULL, Ts = NULL, params, area = 10000)
```

Arguments

Rc	Canopy reflectance at infinite depth
Rg	soil/background reflectance
To	transmission in viewing direction
Ts	transmission in sun direction
params	a named vector of parameters: <ul style="list-style-type: none"> • [1] = D, stand density (confounded with cd) • [2] = cd, crown diameter (confounded with D) • [3] = h, mean crown height • [6] = Solar zenith angle (tts) • [7] = Observer zenith angle (tto) • [8] = Sun-sensor azimuth angle (psi)
area	area of stand

Details

Confounded parameters pairs cannot be inversely estimated, one of the pairs should be set to 1.

Value

a list with reflectance, and the fractions of shaded and sunexposed crowns, shaded and sun exposed open space.

References

Rosema, A., Verhoef, W., Noorbergen, H., Borgesius, J.J. (1992). A new forest light interaction model in support of forest monitoring. *Remote Sens. Environ.* 42, 23-41.

foursail

Optimized R implementation of foursail (4SAIL)

Description

The foursail (or 4SAIL) radiative transfer model is commonly used to simulate bidirectional reflectance distribution functions within vegetation canopies. Foursail (4SAIL) refers to "Scattering by Arbitrary Inclined Leaves" in a 4-stream model. The four-streams represents the scattering and absorption of upward, downward and two directional radiative fluxes with four linear differential equations in a 1-D canopy. The model was initially developed by Verhoef (1984), who extended work by Suits (1971) 4-stream model.

Usage

```
foursail(rho, tau, bgr, param)
```

Arguments

rho	input leaf reflectance from 400-2500nm (can be measured or modeled)
tau	input leaf transmittance from 400-2500nm (can be measured or modeled)
bgr	background reflectance. Usual input is soil reflectance spectra from 400-2500nm (can be measured or modeled)
param	A named vector of SAIL parameter values (note: program ignores case): <ul style="list-style-type: none"> • [1] = Leaf angle distribution function parameter a (LIDFa) • [2] = Leaf angle distribution function parameter b (LIDFb) • [3] = Leaf angle distribution function type (see ?lidfFun) • [4] = Leaf area index (LAI) • [5] = Hot spot effect parameter (hspot) • [6] = Solar zenith angle (tts) • [7] = Observer zenith angle (tto) • [8] = Sun-sensor azimuth angle (psi)

Value

spectra matrix with 4 reflectance factors and canopy transmission for wavelengths 400 to 2500nm:

- [1] = bi-hemispherical reflectance (rddt). White-sky albedo: the reflectance of the canopy under diffuse illumination. The BRDF integrated over all viewing and illumination directions.
- [2] = hemispherical directional reflectance (rsdt). Black-sky albedo: reflectance of a surface under direct light without a diffuse component. It is the integral of the BRDF over all viewing directions.
- [3] = directional hemispherical reflectance (rdot). Diffuse reflectance in the viewing direction.
- [4] = bi-directional reflectance (rsot). The ratio of reflected radiance in the viewing direction to the incoming radiant flux in the solar direction.

- [5] = Canopy transmission of diffuse light through the canopy (τ_{d}).
- [6] = transmission of direct light through the canopy (τ_{s}).

References

- Suits, G.H., 1971. The calculation of the directional reflectance of a vegetative canopy. *Remote Sens. Environ.* 2, 117-125.
- Verhoef, W. (1984). Light scattering by leaf layers with application to canopy reflectance modeling: The SAIL model. *Remote Sens. Environ.* 16, 125-141.

Examples

```
## lower-level implementation example
## see ?fRTM for the typical mode of simulation
## e.g. fRTM(rho~prospectd+foursail)

## 1) get parameters
params<-getDefault(rho~prospectd+foursail)
## getDefault("foursail") will also work
bestpars<-params$foursail$best
## ensure the vector is named
names(bestpars) <- rownames(params$foursail)

## 2) get leaf reflectance and transmission
rt<-fRTM(rho+tau~prospectd)

## 3) get soil reflectance to model background reflectance
data(soil)

## a linear mixture soil model
bgRef<- bestpars["psoil"]*soil[,"drySoil"] + (1-bestpars["psoil"])*soil[,"wetSoil"]

## 4) run 4SAIL
foursail(rt[, "rho"],rt[, "tau"],bgRef,bestpars)
```

foursail2

R implementation of the foursail2 model with 2 canopy layers.

Description

The foursail2 model is a two layer implementation of the foursail model described in Verhoef and Bach (2007). Layers are assumed identical in particle inclination and hotspot, but may differ in the relative density and types of particles (see foursail2b for a layer specific inclination angle). In comparison to foursail, the background (soil), can now be non-Lambertian, having its own 4-stream BDRF (not implemented here but may be input by the user). There are two types of particles, generalized to primary and secondary (originally termed "green" and "brown" particles). The relative abundance of the secondary particle in the top canopy is regulated by the dissociation parameter. The model 4SAIL2 combines with prospect, libery or procosine for the reflectance

and transmittance of the particles, and with the the foursail or Hapke elements for the background reflectance. If run alone, these require direct inputs which could be measured leaf reflectance.

Usage

```
foursail2(rhoA, tauA, rhoB = NULL, tauB = NULL, bgr, rsobgr = NULL,
          rdobgr = NULL, rsdbgr = NULL, rddbgr = NULL, param)
```

Arguments

rhoA	primary particle reflectance from 400-2500nm (can be measured or modeled)
tauA	primary particle transmittance from 400-2500nm (can be measured or modeled)
rhoB	secondary particle reflectance from 400-2500nm (can be measured or modeled)
tauB	secondary particle reflectance from 400-2500nm (can be measured or modeled)
bgr	background reflectance. Usual input is soil reflectance spectra from 400-2500nm (can be measured or modeled)
rsobgr	: background bidirectional reflectance (rso)
rdobgr	: background directional hemispherical reflectance (rdo)
rsdbgr	: background hemispherical directional reflectance (rsd)
rddbgr	: background bi-hemispherical diffuse reflectance (rdd)
param	A named vector of 4SAIL2 parameter values (note: program ignores case): <ul style="list-style-type: none"> • [1] = Leaf angle distribution function parameter a (LIDFa) • [2] = Leaf angle distribution function parameter b (LIDFb) • [3] = Leaf angle distribution function type (TypeLidf, see ?lidfFun) • [4] = Total Leaf Area Index (LAI), including primary and secondary particles (brown and green leaves). • [5] = fraction secondary particles ("brown leaf fraction", fb) • [6] = Canopy dissociation factor for secondary particles ("diss") • [7] = Hot spot effect parameter (hspot). Often defined as the ratio of mean leaf width and canopy height. • [7] = vertical crown coverage fraction (Cv), models clumping in combination with parameter zeta. • [7] = tree shape factor (zeta), defined as the ratio of crown diameter and height. • [6] = Solar zenith angle (tts) • [7] = Observer zenith angle (tto) • [8] = Sun-sensor azimuth angle (psi)

Value

spectra matrix with 4 reflectance factors and canopy transmission for wavelengths 400 to 2500nm:

- [1] = bi-hemispherical reflectance (rddt). White-sky albedo: the reflectance of the canopy under diffuse illumination. The BRDF integrated over all viewing and illumination directions. Diffuse reflectance for diffuse incidence.

- [2] = hemispherical directional reflectance (rsdt). Black-sky albedo: reflectance of a surface under direct light without a diffuse component. It is the integral of the BRDF over all viewing directions. Diffuse reflectance for direct solar incidence.
- [3] = directional hemispherical reflectance (rdot). Diffuse reflectance in the viewing direction.
- [4] = bi-directional reflectance (rsot). The ratio of reflected radiance in the viewing direction to the incoming radiant flux in the solar direction.

References

Verhoef, W., Bach, H. (2007). Coupled soil-leaf-canopy and atmosphere radiative transfer modeling to simulate hyperspectral multi-angular surface reflectance and TOA radiance data. *Remote Sens. Environ.* 109, 166-182.

Examples

```
## see ?foursail for lower-level implementations
fRTM(rho~prospect5+foursail2)
```

foursail2b

R implementation of the foursail2 model with 2 canopy layers.

Description

The foursail2b model is a two layer implementation of the foursail model described in Zhang et al (2005). Layers are assumed identical in hotspot, but may differ in the relative density, inclination and types of particles. In comparison to foursail, the background (soil), can now be non-Lambertian, having its own 4-stream BDRF. There are two types of particles, generalized to primary and secondary (originally termed "green" and "brown" particles). The relative abundance of the secondary particle in the top canopy is regulated by the dissociation parameter. The model 4SAIL2 combines with prospect, libery or procosine for the reflectance and transmittance of the particles, and with the foursail or Hapke elements for the background reflectance. If run alone, these require direct inputs which could be measured leaf reflectance.

Usage

```
foursail2b(rhoA, tauA, rhoB = NULL, tauB = NULL, bgr, rsobgr = NULL,
  rdobgr = NULL, rsdbgr = NULL, rddbgr = NULL, param)
```

Arguments

rhoA	primary particle reflectance from 400-2500nm (can be measured or modeled)
tauA	primary particle transmittance from 400-2500nm (can be measured or modeled)
rhoB	secondary particle reflectance from 400-2500nm (can be measured or modeled)
tauB	secondary particle reflectance from 400-2500nm (can be measured or modeled)

bgr	background reflectance. Usual input is soil reflectance spectra from 400-2500nm (can be measured or modeled)
rsobgr	: background bidirectional reflectance (rso)
rdo bgr	: background directional hemispherical reflectance (rdo)
rsdbgr	: background hemispherical directional reflectance (rsd)
rddbgr	: background bi-hemispherical diffuse reflectance (rdd)
param	A named vector of 4SAIL2 parameter values (note: program ignores case): <ul style="list-style-type: none"> • [1] = Leaf angle distribution function parameter a (LIDFa) • [2] = Leaf angle distribution function parameter b (LIDFb) • [3] = Leaf angle distribution function type (TypeLidf, see ?lidfFun) • [4] = Total Leaf Area Index (LAI), including primary and secondary particles (brown and green leaf). • [5] = fraction secondary particles ("brown leaf fraction", fb) • [6] = Canopy dissociation factor for secondary particles ("diss") • [7] = Hot spot effect parameter (hspot). Often defined as the ratio of mean leaf width and canopy height. • [7] = vertical crown coverage fraction (Cv), models clumping in combination with parameter zeta. • [7] = tree shape factor (zeta), defined as the ratio of crown diameter and height. • [6] = Solar zenith angle (tts) • [7] = Observer zenith angle (tto) • [8] = Sun-sensor azimuth angle (psi)

Value

spectra matrix with 4 reflectance factors and canopy transmission for wavelengths 400 to 2500nm:

- [1] = bi-hemispherical reflectance (rddt). White-sky albedo: the reflectance of the canopy under diffuse illumination. The BRDF integrated over all viewing and illumination directions. Diffuse reflectance for diffuse incidence.
- [2] = hemispherical directional reflectance (rsdt). Black-sky albedo: reflectance of a surface under direct light without a diffuse component. It is the integral of the BRDF over all viewing directions. Diffuse reflectance for direct solar incidence.
- [3] = directional hemispherical reflectance (rdot). Diffuse reflectance in the viewing direction.
- [4] = bi-directional reflectance (rsot). The ratio of reflected radiance in the viewing direction to the incoming radiant flux in the solar direction.

References

Zhang, Q., Xiao, X., Braswell, B., Linder, E., Baret, F., Moore, B. (2005). Estimating light absorption by chlorophyll, leaf and canopy in a deciduous broadleaf forest using MODIS data and a radiative transfer model. *Remote Sens. Environ.* 99, 357-371.

Examples

```
## see ?foursail for lower-level implementations
fRTM(rho~prospectd+foursail2b)
```

fRTM

*Forward implementation of coupled Radiative Transfer Models.***Description**

Forward implementation of coupled Radiative Transfer Models.

Usage

```
fRTM(fm = rho + tau ~ prospect5 + foursail, pars = NULL,
      wl = 400:2500)
```

Arguments

fm	A formula specifying which rtm to run
pars	a list of <code>_named_</code> parameter vectors for all models. The parameter list for a model call as <code>rho ~ prospect + foursail</code> therefore contains two named vectors the first with parameters for prospect and the second with parameters for foursail if left empty default parameters are generated
wl	wavelengths (in nm) add only if certain wavelengths are required as output. Input is expected to integers between 400 and 2500, or will be forced to be an integer. Integers outside the 400:2500 range will not be returned.

Value

spectra matrix with reflectance (and transmission, depending on the formula inputs). See separate model helpfiles for details.

Examples

```
## setup graphics for plots
oldpar<-par()
par(mfrow=c(3,2))

## get reflectance for a leaf
ref <- fRTM(rho~prospect5)
plot(ref,main="Prospect 5")

## get reflectance and transmission for a leaf
reftrans <- fRTM(rho+tau~prospect5)
plot(reftrans,main="Prospect 5")

## get reflectance for a single layered canopy
```

```

ref <- fRTM(rho~prospect5+foursail)
plot(ref,main="Prospect 5 + 4SAIL")

## get reflectance for a 2 layered canopy with two leaf types
ref <- fRTM(rho~prospectd+prospect5+foursail2)
plot(ref,main="Prospect D + Prospect 5 + 4SAIL2")

## edit the parameters: sparse vegetation LAI
parlist<- list(prospect5=NULL,prospectd=NULL,foursail2=c(LAI=0.05))

## update reflectance
ref <- fRTM(rho~prospect5+prospectd+foursail2,parlist)
plot(ref,main="LAI=0.05")

## change leaf area index to dense vegetation
parlist$foursail2["LAI"]<-8.5

## update reflectance
ref <- fRTM(rho~prospect5+prospectd+foursail2,parlist)
plot(ref,main="LAI=8.5")

par(oldpar)

```

getDefaults

S3- methods for Generate defaults settings and parameters for all supported models.

Description

S3- methods for Generate defaults settings and parameters for all supported models.

Usage

```
getDefaults(model = NULL, ...)
```

Arguments

model	a crrtm formula or character vector of modelnames
...	not used. (e.g. "prospect5")

Value

a data.frame with default model parameters

KLd	<i>Kullback-Lieber divergence function $D(\text{spec1} \parallel \text{spec2}) = \text{sum}(\text{spec1} * \log(\text{spec1} / \text{spec2}))$</i>
-----	---

Description

Kullback-Lieber divergence function $D(\text{spec1} \parallel \text{spec2}) = \text{sum}(\text{spec1} * \log(\text{spec1} / \text{spec2}))$

Usage

KLd(spec1, spec2)

Arguments

spec1	spectral signal 1
spec2	spectral signal 2 at identical wavelengths

Value

the KL divergence between the vector inputs

lidf	<i>Leaf inclination distribution models s3 method for calling leaf models</i>
------	---

Description

Leaf inclination distribution models s3 method for calling leaf models

Usage

lidf(pars)

Arguments

pars	a parameter vector with a class lidf.[modelnumber]. Models include: <ul style="list-style-type: none"> • [1] = Dlagden distribution (1, lidf.1) • [2] = Ellipsoid (Campebl) distribution (2, lidf.2) • [3] = Beta distribution (3, lidf.3) • [4] = One parameter beta distribution (4, lidf.4)
------	--

Models 1 and 2 are the standard models from the SAIL model

Value

a vector of proportions for each leaf angle calculated from each leaf inclination model

plot.rtm.spectra *Plot RTM return spectra vs. wavelength*

Description

Plot RTM return spectra vs. wavelength

Usage

```
## S3 method for class 'rtm.spectra'  
plot(x, ...)
```

Arguments

x predictions from an RTM
... additional plot arguments

Value

plots to the device a ccrtm standard spectra plot based on the function call returned from fRTM.

print.rtm.spectra *Plot RTM return spectra vs. wavelength*

Description

Plot RTM return spectra vs. wavelength

Usage

```
## S3 method for class 'rtm.spectra'  
print(x, ...)
```

Arguments

x predictions from an RTM
... additional plot arguments

Value

prints the standard information from a simulated ccrtm spectra plot

prospect5

*PROSPECT model version 5 and 5B***Description**

The PROSPECT5(b) leaf reflectance model. The model was implemented based on Jacquemoud and Ustin (2019), and is further described in detail in Feret et al (2008). PROSPECT models use the plate models developed in Allen (1969) and Stokes (1862). Set Cbrown to 0 for prospect version 5.

Usage

prospect5(param)

Arguments

param A named vector of PROSPECT parameters (note: program ignores case):

- [1] = leaf structure parameter (N)
- [2] = chlorophyll a+b content in ug/cm2 (Cab)
- [3] = carotenoids content in ug/cm2 (Car)
- [4] = brown pigments content in arbitrary units (Cbrown)
- [5] = equivalent water thickness in g/cm2 (Cw)
- [6] = leaf dry matter content in g/cm2 - lma - (Cm)

Value

spectra matrix with leaf reflectance and transmission for wavelengths 400 to 2500nm:

- [1] = leaf reflectance (rho)
- [2] = leaf transmission (tau)

References

- Jacquemoud, S., and Ustin, S. (2019). Leaf optical properties. Cambridge University Press.
- Feret, J.B., Francois, C., Asner, G.P., Gitelson, A.A., Martin, R.E., Bidel, L.P.R., Ustin, S.L., le Maire, G., Jacquemoud, S. (2008), PROSPECT-4 and 5: Advances in the leaf optical properties model separating photosynthetic pigments. Remote Sens. Environ. 112, 3030-3043.
- Allen W.A., Gausman H.W., Richardson A.J., Thomas J.R. (1969), Interaction of isotropic lighth with a compact plant leaf, Journal of the Optical Society of American, 59:1376-1379.
- Stokes G.G. (1862), On the intensity of the light reflected from or transmitted through a pile of plates, Proceedings of the Royal Society of London, 11:545-556.

prospectd

*PROSPECT model version D***Description**

The PROSPECTD leaf reflectance model. The model was implemented based on Jacquemoud and Ustin (2019), and is further described in detail in Feret et al (2017). PROSPECT models use the plate models developed in Allen (1969) and Stokes (1862).

Usage

prospectd(param)

Arguments

param A named vector of PROSPECT parameters (note: program ignores case):

- [1] = leaf structure parameter (N)
- [2] = chlorophyll a+b content in ug/cm2 (Cab)
- [3] = carotenoids content in ug/cm2 (Car)
- [4] = Leaf anthocyanin content (ug/cm2) (Canth)
- [5] = brown pigments content in arbitrary units (Cbrown)
- [6] = equivalent water thickness in g/cm2 (Cw)
- [7] = leaf dry matter content in g/cm2 - lma - (Cm)

Value

spectra matrix with leaf reflectance and transmission for wavelengths 400 to 2500nm:

- [1] = leaf reflectance (rho)
- [2] = leaf transmission (tau)

References

- Jacquemoud, S., and Ustin, S. (2019). Leaf optical properties. Cambridge University Press.
- Feret, J.B., Gitelson, A.A., Noble, S.D., Jacquemoud, S. (2017). PROSPECT-D: Towards modeling leaf optical properties through a complete lifecycle. Remote Sens. Environ. 193, 204-215.
- Allen W.A., Gausman H.W., Richardson A.J., Thomas J.R. (1969), Interaction of isotropic lighth with a compact plant leaf, Journal of the Optical Society of American, 59:1376-1379.
- Stokes G.G. (1862), On the intensity of the light reflected from or transmitted through a pile of plates, Proceedings of the Royal Society of London, 11:545-556.

r_foursail

R implementation of foursail (pure R)

Description

The pure R version of foursail is included in the package as an easy way to review the code, and to check more optimized versions against. Model originally developed by Wout Verhoef.

Usage

```
r_foursail(rho, tau, bgr, param)
```

Arguments

rho	input leaf reflectance from 400-2500nm (can be measured or modeled)
tau	input leaf transmittance from 400-2500nm (can be measured or modeled)
bgr	background reflectance. Usual input is soil reflectance spectra from 400-2500nm (can be measured or modeled)
param	A named vector of SAIL parameter values (note: program ignores case): <ul style="list-style-type: none"> • [1] = Leaf angle distribution function parameter a (LIDFa) • [2] = Leaf angle distribution function parameter b (LIDFb) • [3] = Leaf angle distribution function type (see ?lidfFun) • [4] = Leaf area index (LAI) • [5] = Hot spot effect parameter (hspot) - The foliage hot spot size parameter is equal to the ratio of the correlation length of leaf projections in the horizontal plane and the canopy height (Verhoef & Bach 2007). • [6] = Solar zenith angle (tts) • [7] = Observer zenith angle (tto) • [8] = Sun-sensor azimuth angle (psi)

Value

spectra matrix with 4 reflectance factors and canopy transmission for wavelengths 400 to 2500nm:

- [1] = bi-hemispherical reflectance (rddt). White-sky albedo: the reflectance of the canopy under diffuse illumination. The BRDF integrated over all viewing and illumination directions.
- [2] = hemispherical directional reflectance (rsdt). Black-sky albedo: reflectance of a surface under direct light without a diffuse component. It is the integral of the BRDF over all viewing directions.
- [3] = directional hemispherical reflectance (rdot). Diffuse reflectance in the viewing direction.
- [4] = bi-directional reflectance (rsot). The ratio of reflected radiance in the viewing direction to the incoming radiant flux in the solar direction.
- [5] = Canopy transmission of diffuse light through the canopy (taud).
- [6] = transmission of direct light through the canopy (taus).

Author(s)

Marco D. Visser (R implementation)

sail_BDRF

The SAIL BDRF function

Description

The SAIL BDRF function

Usage

```
sail_BDRF(w, lai, sumint, tsstoo, rsoil, rdd, tdd, tsd, rsd, tdo, rdo, tss,
          too, rsod)
```

Arguments

w	geometric reflectance parameter
lai	leaf area index
sumint	exp int
tsstoo	Bi-directional gap fraction
rsoil	background reflectance
rdd	Bi-hemispherical reflectance over all in & outgoing directions (white-sky albedo).
tdd	Bi-hemispherical transmittance (diffuse transmittance in all directions)
tsd	Directional hemispherical transmittance for solar flux
rsd	Directional hemispherical reflectance for solar flux (diffuse solar angle)
tdo	Directional hemispherical transmittance (diffuse in viewing direction)
rdo	Directional hemispherical reflectance in viewing direction
tss	Direct transmittance of solar flux
too	Direct transmittance in viewing direction
rsod	Multi scattering contribution

Value

spectra matrix with 4 reflectance factors and canopy transmission for wavelengths 400 to 2500nm:

- [1] = bi-hemispherical reflectance (rddt). White-sky albedo: the reflectance of the canopy under diffuse illumination. The BRDF integrated over all viewing and illumination directions.
- [2] = hemispherical directional reflectance (rsdt). Black-sky albedo: reflectance of a surface under direct light without a diffuse component. It is the integral of the BRDF over all viewing directions.
- [3] = directional hemispherical reflectance (rdot). Diffuse reflectance in the viewing direction.

- [4] = bi-directional reflectance (rsot). The ratio of reflected radiance in the viewing direction to the incoming radiant flux in the solar direction.
- [5] = Canopy transmission of diffuse light through the canopy (taud).
- [6] = transmission of direct light through the canopy (taus).

 skyl

Sky light model

Description

Simple atmospheric model that builds on recommendations from Francois et al. (2002).

Usage

```
skyl(rddt, rsdt, rdot, rsot, Es, Ed, tts, skyl = NULL)
```

Arguments

rddt	Bi-hemispherical reflectance
rsdt	Directional-hemispherical reflectance for solar incident flux
rdot	Hemispherical-directional reflectance in viewing direction
rsot	Bi-directional reflectance factor
Es	Solar flux
Ed	Diffuse flux
tts	solar angle
skyl	fraction diffuse

Value

a list with hemispherical and directional reflectance. `rt<-fRTM(rho~prospect5+foursail) skyl(rt[,"rddt"],rt[,"rsdt"],rt[,"rdot"],Es=solar[,1],Ed=solar[,2],tts=45,skyl=NULL)`

References

Francois, C., Otte, C., Olioso, A., Prevot, L., Bruguier, N., Ducros, Y.(2002). Conversion of 400-1100 nm vegetation albedo measurements into total shortwave broadband albedo using a canopy radiative transfer model. *Agronomie* 22, 611-618.

Examples

```
data(solar)
```

 soil

soil reflectance

Description

soil reflectance

Usage

data(soil)

details

- [1] = wet soil
- [2] = dry soil

references

Feret et al. (2008), PROSPECT-4 and 5: Advances in the Leaf Optical Properties Model Separating Photosynthetic Pigments, Remote Sensing of Environment

solar

direct and diffuse light

Description

direct and diffuse light

Usage

data(solar)

details

- [1] = direct light
- [2] = diffuse light

references

Feret et al. (2008), PROSPECT-4 and 5: Advances in the Leaf Optical Properties Model Separating Photosynthetic Pigments, Remote Sensing of Environment

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