

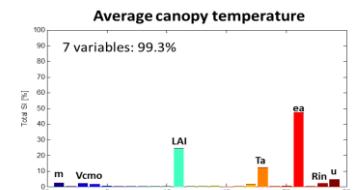
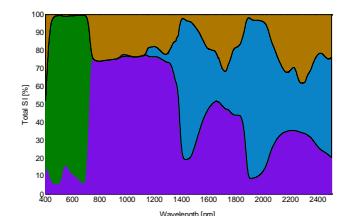
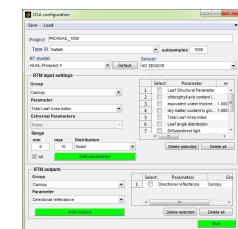
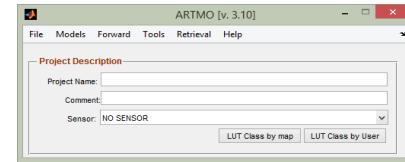
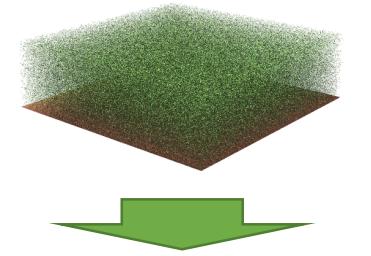
ARTMO's Global Sensitivity Analysis (GSA) toolbox to quantify driving variables of leaf and canopy radiative transfer models

J. Verrelst, J.P. Rivera & J. Moreno

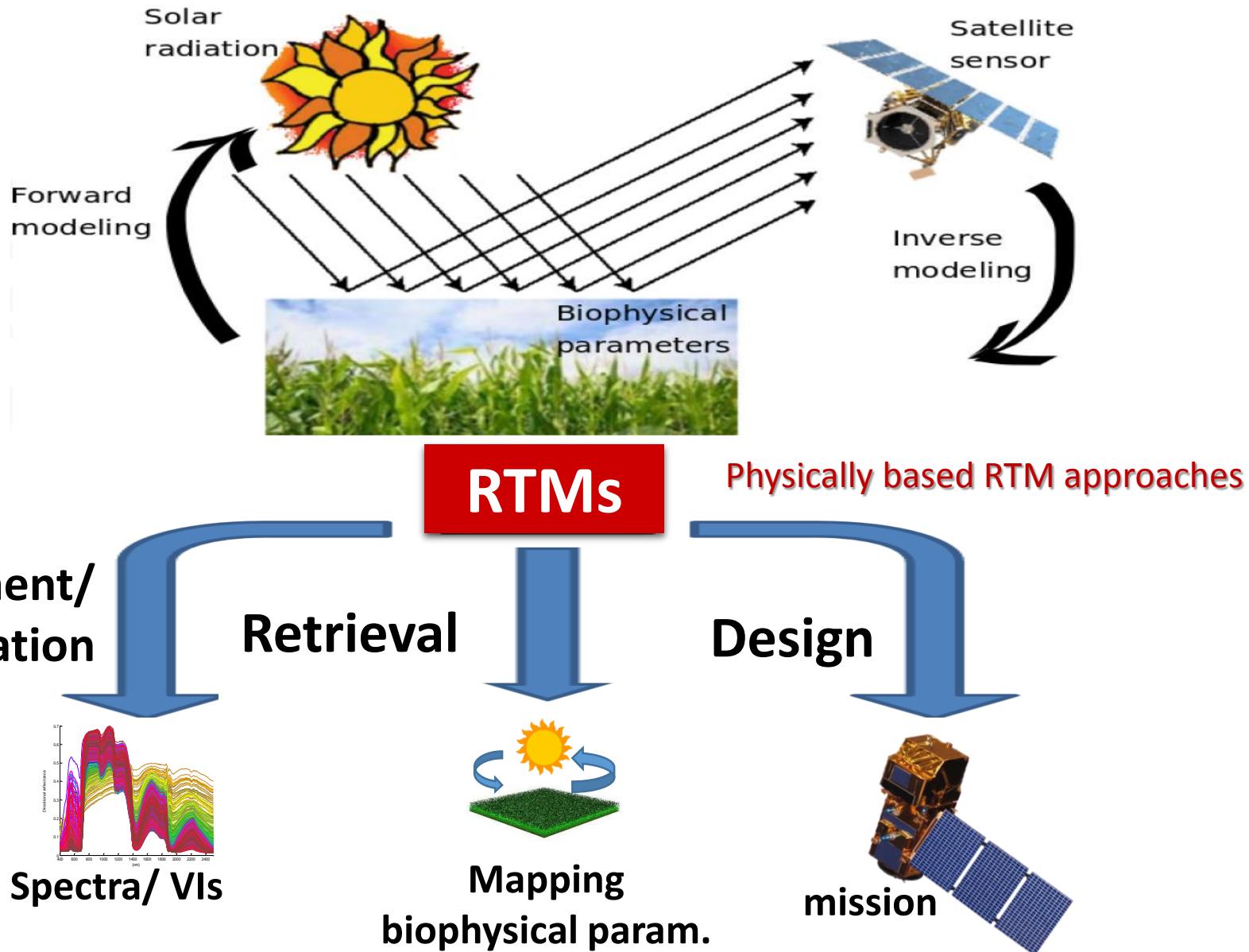
15/04/2015 – 9th EARSeL SIG IS

Outline:

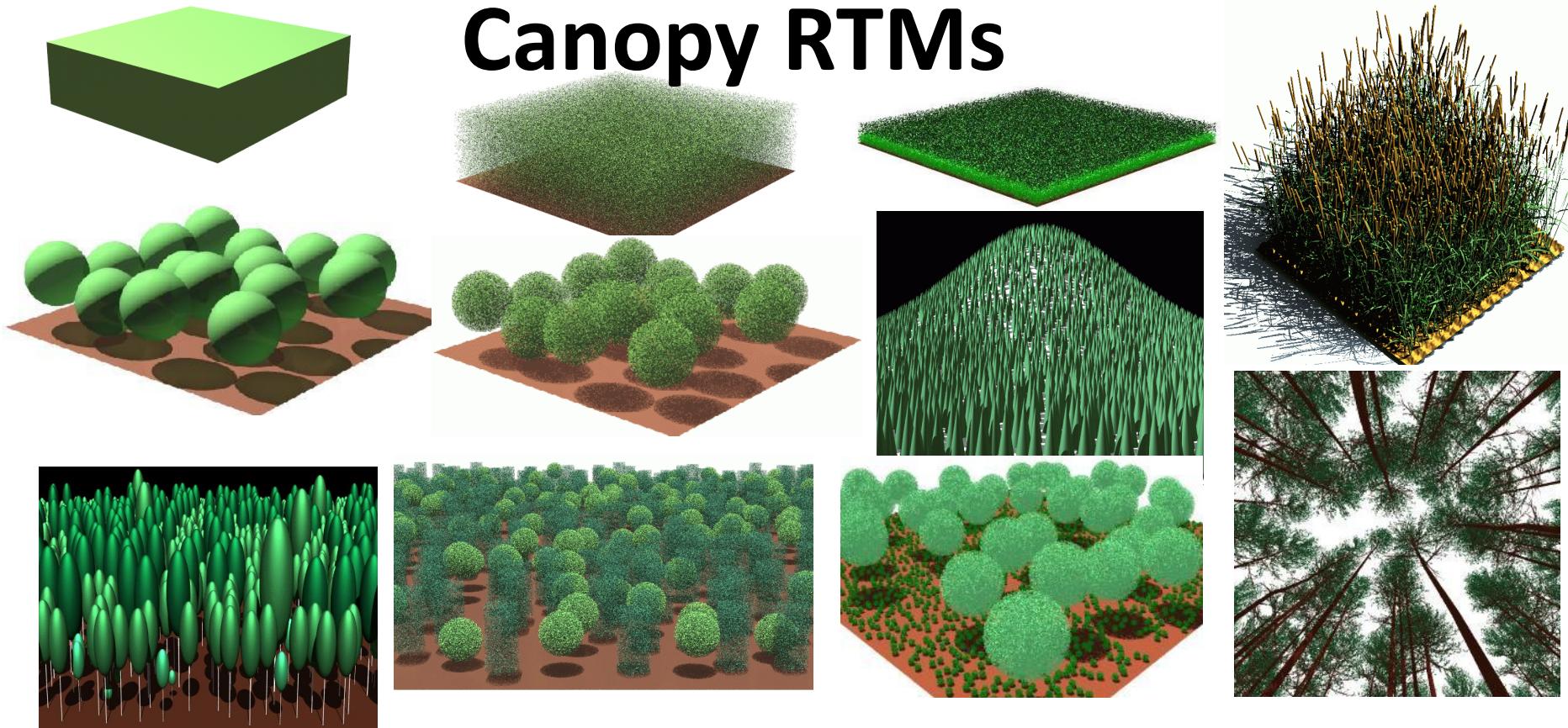
- Background RTM
- GSA theory
- ARTMO's RTMs
- ARTMO's GSA toolbox
- GSA toolbox results
 - Leaf
 - Leaf + canopy
 - SVAT model SCOPE
- Conclusions



Background



Canopy RTMs



- RTMs vary in **design, complexity, number of input variables, processing speed**.
- **Not all RTM input variables play an equally important role**; they are also spectrally dependent.
- For the larger majority of RS applications **there is no need to vary all variables!**

How to identify key RTM input variables, and variables that can be safely set to default values?

Global sensitivity analysis (GSA)

Sensitivity analysis evaluates the relative importance of each input parameter and can be used to identify the most influential parameters in determining the variability of model outputs.

1. Local sensitivity analysis: “One-factor-at-a-time” (OAT): changing one input parameter at a time whilst holding all other at their central values . AOT methods do not cover the whole input parameter space. → Inadequate for analyzing complex models which may have many parameters and may be high-dimensional and/or non-linear.
2. Global sensitivity analysis: explores the full input parameter space. The contribution of each input parameter to the variation in outputs is averaged over the variation of all input parameters, i.e. all input parameters are changed together.

GSA techniques, which quantify the relative importance of each input parameter to model outputs, can help set safe default values for those less influential input parameters.

GSA can greatly simplify model calibration through enabling the most influential parameters to be targeted for data acquisition and refinement.

Variance-based methods - Global sensitivity indices

Variance-based method: the output variance is decomposed to the sum of contributions of each individual input parameter and the interactions (coupling terms) between different parameters.

Based on the work of Sobol', **variance-based sensitivity measures** are represented as follows:

$$1 = \sum_i S_i + \sum_i \sum_{j>i} S_{ij} + \dots + S_{12,\dots,k},$$

in this equation, $S_i, S_{ij}, \dots, S_{12,\dots,k}$ are **Sobol's global sensitivity indices**.:

- The **first order sensitivity index** S_i , measures and quantifies the sensitivity of model output Y to the input parameter X_i (**without interaction terms**), whereas, $S_{ij}, \dots, S_{12,\dots,k}$ are the sensitivity measures for the higher order terms (interaction terms).
- The **total effect sensitivity index** S_{Ti} measures **the whole effect of the variable X_i** , i.e. the first order effect as well as its coupling terms with the other input variables:

$$S_{Ti} = S_1 + S_{12} + S_{13} + S_{123}$$

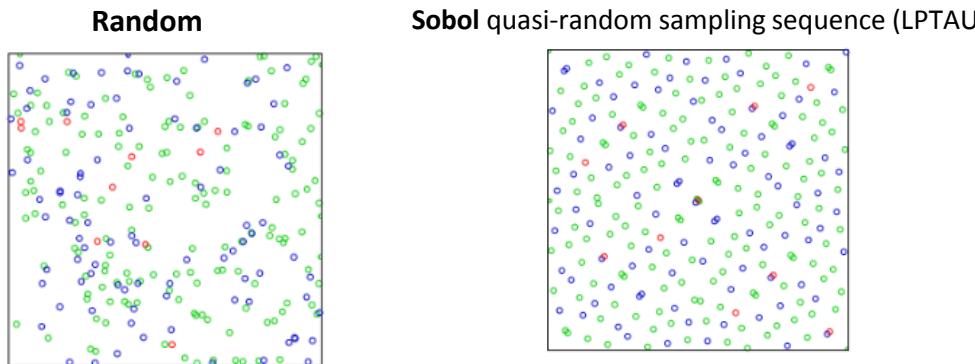
Sobol', I.M., (2001). Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates, Mathematics and Computers in Simulation, 55(1-3), 271- 280

GSA method of Saltelli et al., 2010:

• **First order sensitivity:** $S_i = \frac{\frac{1}{n} \sum_{j=1}^n f(B)_j \left(f(A_B^i)_j - f(A)_j \right)}{\text{Var}(L)}$

• **Total sensitivity:** $S_{II} = \frac{\frac{1}{2n} \sum_{j=1}^n \left(f(A)_j - f(A_B^i)_j \right)^2}{\text{Var}(L)}$

Sample distribution:



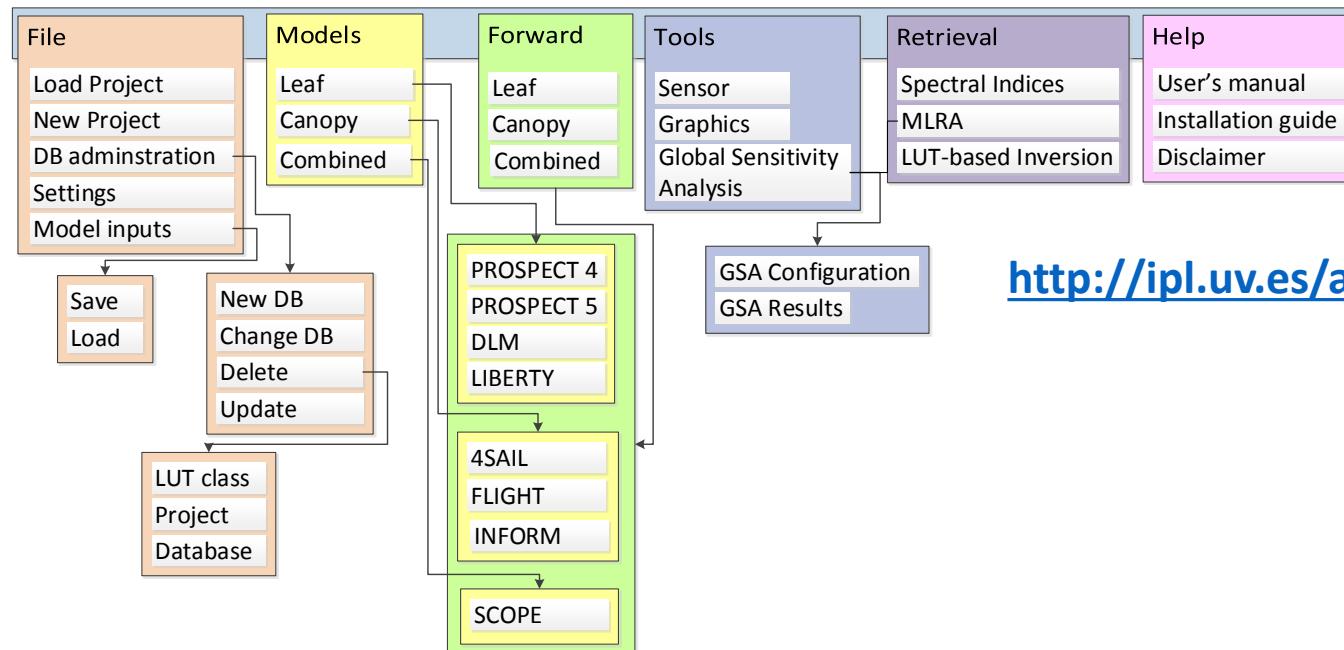
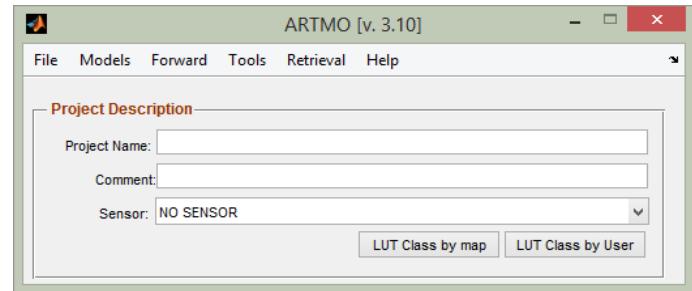
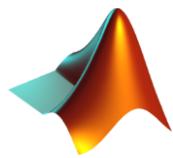
Total # of samples = $(N_{\text{variables}} + 2) * \# \text{sample distribution}$



These methods are hard to use – no GSA code publicly available to RTM analysis

Need for a dedicated toolbox!

Availability of RTMs:



<http://ipl.uv.es/artmo/>

ARTMO seems perfectly suited to develop a GSA toolbox.

ARTMO's RTMs:

T. Dawson

Leaf RTMs

S. Jacquemoud & JP Féret

PROSPECT 4

Select LUT Class: Generic class

Leaf Structure (N) [1-4]	Chlorophyll (Cab - $\mu\text{g}/\text{cm}^2$) [0-100]
1.5	30
<input type="checkbox"/> Range	<input type="checkbox"/> Table
Water thickness (Cw - cm) [0-0.05]	Dry matter (Cm - g/cm^2) [0-0.05]
0.03	0.012
<input type="checkbox"/> Range	<input type="checkbox"/> Table

OK

PROSPECT 5

Select LUT Class: Generic class

Leaf Structure (N) [1-4]	Chlorophyll (Cab- $\mu\text{g}/\text{cm}^2$) [0-100]
1.5	50
<input type="checkbox"/> Range	<input type="checkbox"/> Table
Carotenoids ($\mu\text{g}/\text{cm}^2$)	Brown Pigments
0	0
<input type="checkbox"/> Range	<input type="checkbox"/> Table
Water thickness (Cw-cm) [0-0.05]	Dry matter (Cm - g/cm^2) [0-0.05]
0.003	0.012
<input type="checkbox"/> Range	<input type="checkbox"/> Table

OK

LIBERTY

Select LUT Class: Generic class

Cell Diameter [20-100]	Chlorophyll content ($\mu\text{g}/\text{cm}^2$) [0-500]
40	200
<input type="checkbox"/> Range	<input type="checkbox"/> Table
Intercellular air space [0.01-0.1]	Water content (g/m^2) [0-500]
0.045	100
<input type="checkbox"/> Range	<input type="checkbox"/> Table
Leaf thickness [1-10]	Lignin & Cellulose (g/m^2) [10-80]
1.6	40
<input type="checkbox"/> Range	<input type="checkbox"/> Table
Baseline [Fresh: 0.0006 - Dry: 0.0004]	Nitrogen content (g/m^2) [0.3-2]
0.0006	1
<input type="checkbox"/> Range	<input type="checkbox"/> Table
Albino absorption [0-4]	f. Pigm. in palisade [0-1]
2	0.003
<input type="checkbox"/> Range	<input type="checkbox"/> Table

OK

Dorsiventral Leaf Model - DLM

Select LUT Class: Generic class

Chlorophyll ($\mu\text{g}/\text{cm}^2$) [0-150]	Water thickness (cm^{-1}) [0-0.05]
60	0.02
<input type="checkbox"/> Range	<input type="checkbox"/> Table
Dry matter (g/cm^2) [0-0.05]	Carotenoids ($\mu\text{g}/\text{cm}^2$)
0.01	0
<input type="checkbox"/> Range	<input type="checkbox"/> Table
Brown Pigments [0-5]	Structure parameters
0	f. air spaces [0-1]
<input type="checkbox"/> Range	0.5
<input type="checkbox"/> Table	<input type="checkbox"/> Range
<input type="checkbox"/> Table	0.003
<input type="checkbox"/> Table	<input type="checkbox"/> Table
<input type="checkbox"/> Table	f. total mass in pal. [0-1]
<input type="checkbox"/> Table	0.012
<input type="checkbox"/> Table	<input type="checkbox"/> Range
<input type="checkbox"/> Table	0
<input type="checkbox"/> Table	<input type="checkbox"/> Table
<input type="checkbox"/> Table	roughness factor [0-2]
<input type="checkbox"/> Table	0
<input type="checkbox"/> Table	<input type="checkbox"/> Table
<input type="checkbox"/> Table	Abaxial scattering [0-0.99]
<input type="checkbox"/> Table	0
<input type="checkbox"/> Table	<input type="checkbox"/> Table

OK

Outputs: reflectance & transmittance

Canopy RTMs

W. Vehoef

4SAIL

Select LUT Class: Generic class

LAI [0-10]	Hot spot effect [0 - 1]
3	0.01
<input type="checkbox"/> Range	<input type="checkbox"/> Table
Average leaf angle ($^{\circ}$) [0 - 90]	Solar zenith angle ($^{\circ}$) [0 - 90]
30	0
<input type="checkbox"/> Range	<input type="checkbox"/> Table
Diffuse/Direct radiation [0 - 100]	Observer zenith angle ($^{\circ}$) [-75 - 75]
10	0
<input type="checkbox"/> Range	<input type="checkbox"/> Table
Soil coefficient [0 - 1]	Azimuth ($^{\circ}$) [0 - 180]
0	0
<input type="checkbox"/> Range	<input type="checkbox"/> Table

OK

FLIGHT

Select LUT Class: Generic class

Dimension	Mode of operation	Number of photons	Number of bands
<input checked="" type="radio"/> 1D	<input checked="" type="radio"/> REVERSE	Photons: 10000	Bands: <input type="text"/>
Solar Angle	AOT @ 550 nm	Soil roughness index [0-1]	
Zenith	0.08	0	<input type="checkbox"/> Range
Azimuth	<input type="checkbox"/> Range	<input type="checkbox"/> Table	
View Angle	Leaf size [0-1]	LAI	
Zenith	0.01	1	<input type="checkbox"/> Range
Azimuth	<input type="checkbox"/> Range	<input type="checkbox"/> Table	
FGL	FVC	Crown Shape	
Fraction of green leaves	0.2	<input checked="" type="radio"/> Ellipsoid	<input type="checkbox"/> Cones
% Fraction of 'senescent/shoot'	0.22	<input type="checkbox"/> Field data	
Remaining fraction will go to 'bark'	50		
LAD	Planophile	Crown geo parameters	
[0-10]:	0.22	Crown radius: 0.880	
[20-30]:	0.182	Centre to top distance: 4.929	
[40-50]:	0.111	Height to first branch:	
[60-70]:	0.04	Min: 4.1	
[80-90]:	0.003	Max: 9.9	
	30	Trunk DBH: 0.179	

OK

Outputs: directional reflectance

P. North

C. Atzberger & M. Schlerf

INFORM [v. 1.00]

Select LUT Class: Generic class

Canopy geometry	
Single tree LAI [0-10]	LAI of understorey [0-3]
5	1
<input type="checkbox"/> Range	<input type="checkbox"/> Table
Stem density [ha^{-1}] [0 - 1000]	Average leaf angle [deg] [15-75]
300	55
<input type="checkbox"/> Range	<input type="checkbox"/> Table
Tree height [m] [0-50]	Crown diameter [m] [0 - 10]
20	3
<input type="checkbox"/> Range	<input type="checkbox"/> Table
Sun-object-sensor geometry	
Solar zenith angle ($^{\circ}$) [0 - 90]	Relative azimuth ($^{\circ}$) [0 - 180]
30	90
<input type="checkbox"/> Range	<input type="checkbox"/> Table
Observer zenith angle ($^{\circ}$) [0 - 90]	Fraction of diffuse radiation [0-1]
0	0.1
<input type="checkbox"/> Range	<input type="checkbox"/> Table

OK

Combined: SCOPE

The figure displays six MATLAB graphical user interface (GUI) windows for the SCOPE model:

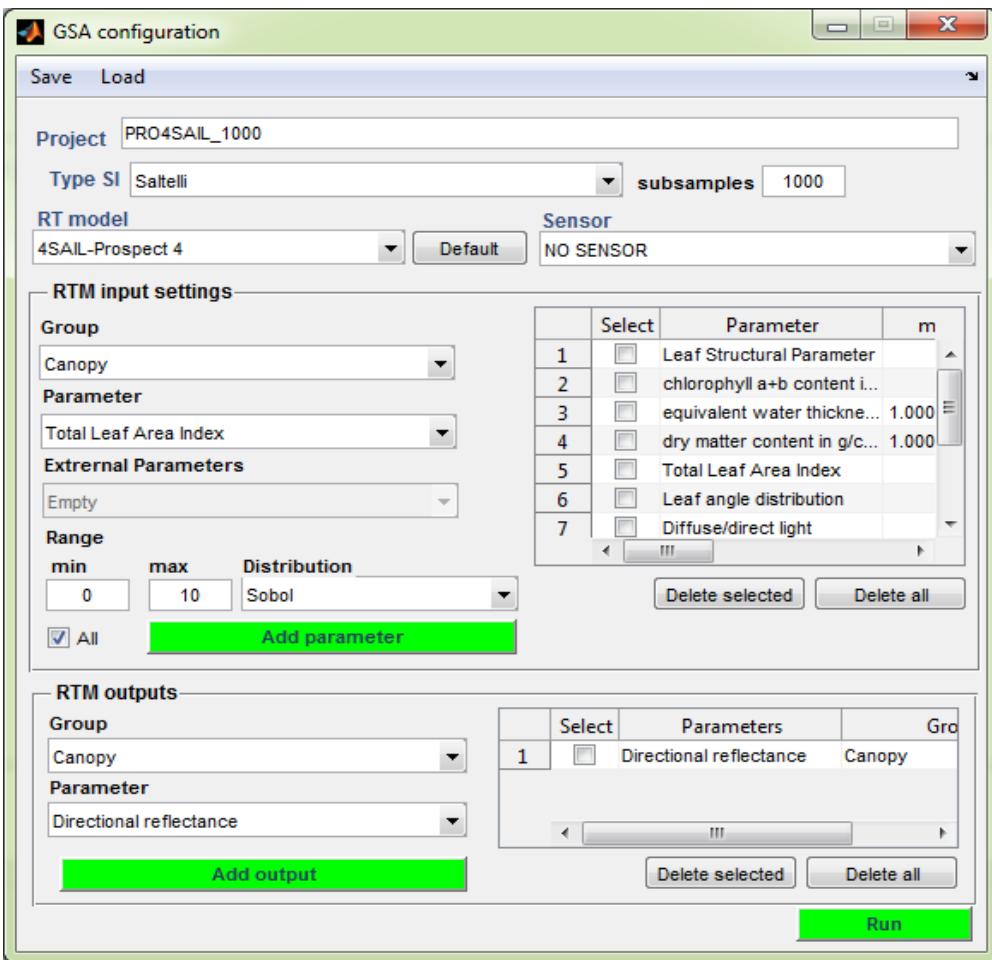
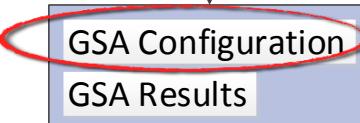
- scope_gui_mod2**: Leaf - Biochemical [Von Cammerer-MD12]. This window contains parameters for photosynthetic pathway (c3), maximum carboxylation capacity (0-200), Ball-Berry stomatal conductance (2-20), Rdparam (0.001-0.1), qLs, kNPsOs (s-1), and extinction coefficient for Vcmax (0-0.8).
- scope_gui_mod7**: Leaf parameters. This window shows leaf parameters for Green Leaf, including Leaf Structure (N) [1-3] (1.4), Chlorophyll (Cab - $\mu\text{g}/\text{cm}^2$) [0-100] (40), Water thickness (Cw - cm) [0-0.5] (0.009), Dry matter (Cm - g/cm^2) [0-0.05] (0.012), and Senescent material [0-0.3] (0). It also includes broadband thermal reflectance (0.01) and broadband thermal transmittance (0.01).
- 4SAIL MODEL**: Canopy geometry. This window includes LAI [0-10+] (3), vegetation height (h) [m] [0.05 - 100] (0.5), leaf width [m] [0.01 - 2] (0.1), and leaf inclination distribution function (with categories: Erectophile, Plagiophile, Extremophile, Spherical, Uniform, User, where Spherical is selected).
- 4SAIL MODEL**: Soil Parameters. This window lists ID_soil (Soil_ColumnID1, Soil_ColumnID2, Soil_ColumnID3), soil resistance for evaporation (200-5000 s m^{-1}) (500), volumetric soil moisture content (0.01 - 0.7) (0.25), broadband soil reflectance in the thermal range (0.06), volumetric heat capacity of the soil ($\text{J m}^{-2} \text{K}^{-1}$) (1180), specific mass of the soil (kg m^{-3}) (1800), and heat conductivity of the soil ($\text{J m}^{-1} \text{K}^{-1}$) (1.55).
- Angular geometry**: This window shows angular geometry parameters: Solar zenith angle ($^{\circ}$) [0 - 90] (30), Observer zenith angle ($^{\circ}$) [0 - 90] (0), and Relative azimuth ($^{\circ}$) [0 - 180] (90).
- scope_gui_mod6**: Weather conditions. This window lists incoming shortwave radiation [W m^{-2}] (600), air temperature [$^{\circ}\text{C}$] (20), atmospheric vapour pressure [hPa] (15), CO₂ concentration in the air [ppm] (380), incoming longwave radiation [W m^{-2}] (350), air pressure [hPa] (1000), wind speed [m s^{-1}] (2), O₂ concentration in the air [ppm] (209), and measurement height of meteorological data [m] (10).

SCOPE is an energy balance model and provides over 50 outputs, grouped according to: aerodynamic, fluxes (e.g. PAR), radiation, reflectance, spectrum, surface temperature, fluorescence.

More about SCOPE see Fluorescence session

GSA Configuration

ARTMO→Tools → Global Sensitivity Analysis



- Give a **Project** name
- Select GSA (**Saltelli (2010)**, EFAST, Sobol)
- **# Subsamples**
- Select **RTM**. Option to select a **Sensor**.
- Select **RTM input variables**, boundaries and sampling distribution.
- Select **RTM output**: *multiple variables at once can be analyzed*.

The following RTM combinations have been implemented:

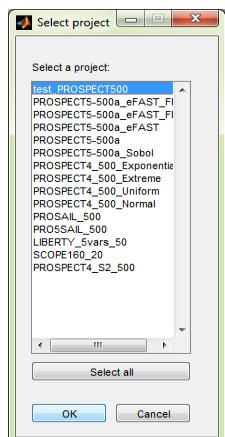
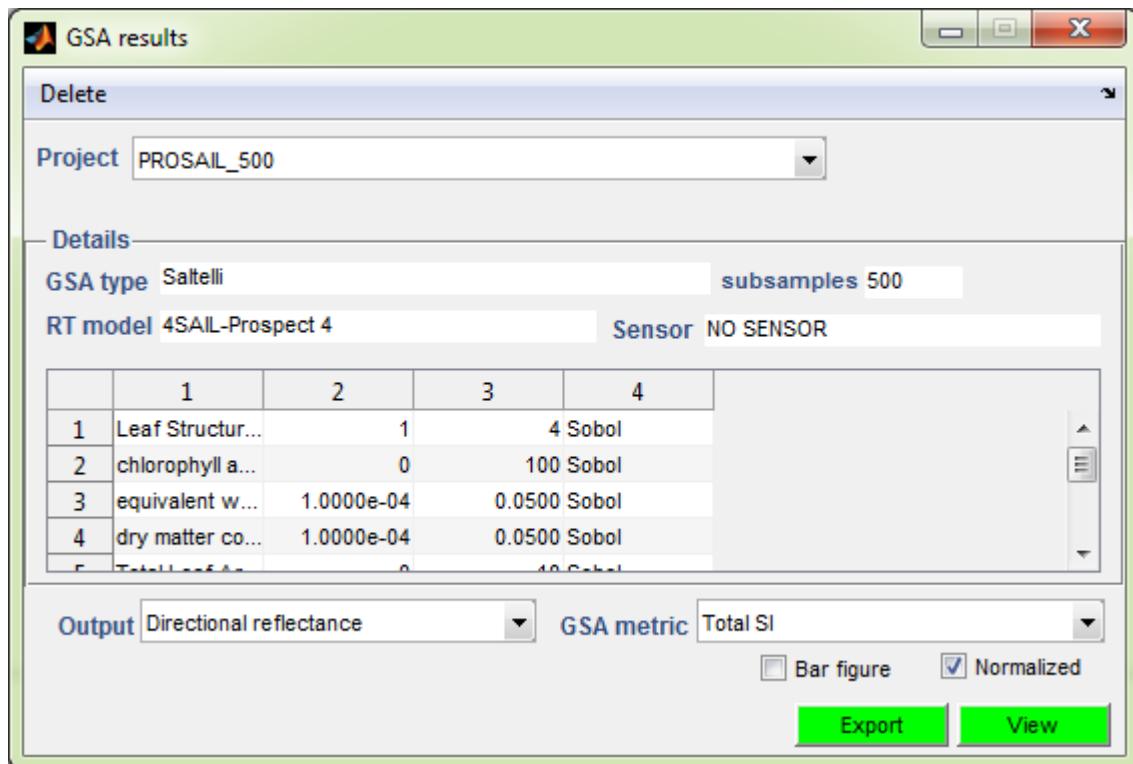
Leaf: PROSPECT4, PROSPECT5, DLM, LIBERTY,

Leaf + canopy: PROSPECT4-SAIL, PROSPECT5-SAIL, LIBERTY-SAIL, PROSPECT4-INFORM, PROSPECT5-INFORM, LIBERTY-INFORM, SCOPE

GSA results

ARTMO→Tools → Global Sensitivity Analysis

GSA Configuration
GSA Results



- **Project name**
- **GSA & RTM info**
- Overview of **input variables**, boundaries and sampling distribution
- Select **output variables** to visualize or export.
- Select **first** or **total** order **sensitivity indices**.

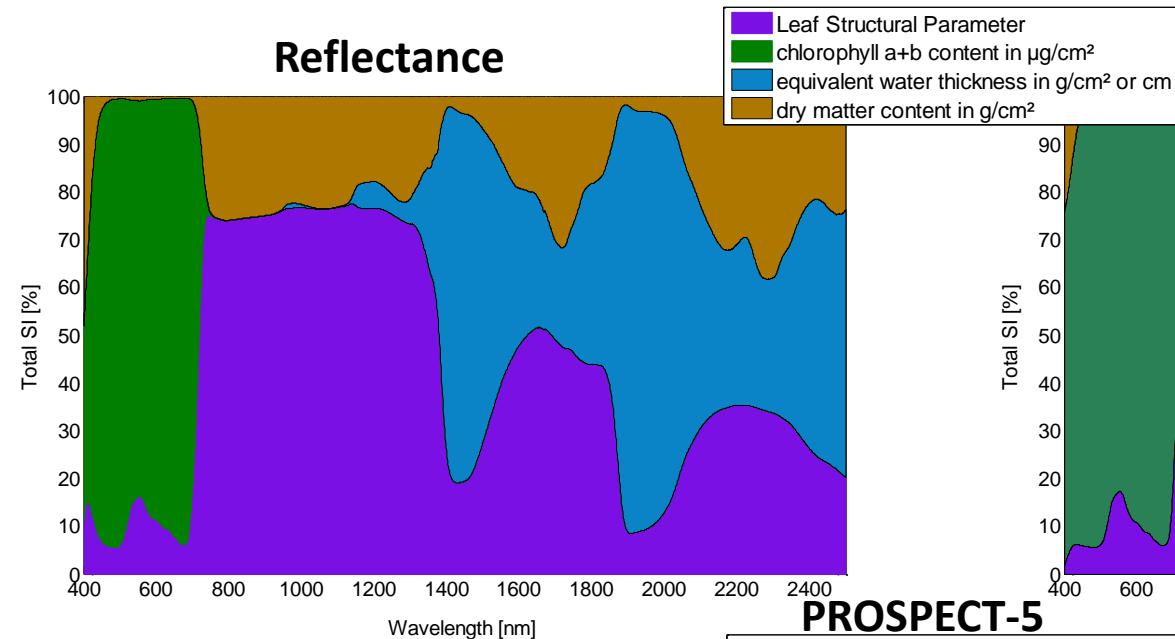
Sensitivity indices results are stored in MySQL database. That allows fast visualizing or deleting of earlier results.

Speed bottleneck is the RTM (e.g. SCOPE) – GSA results fastly generated.

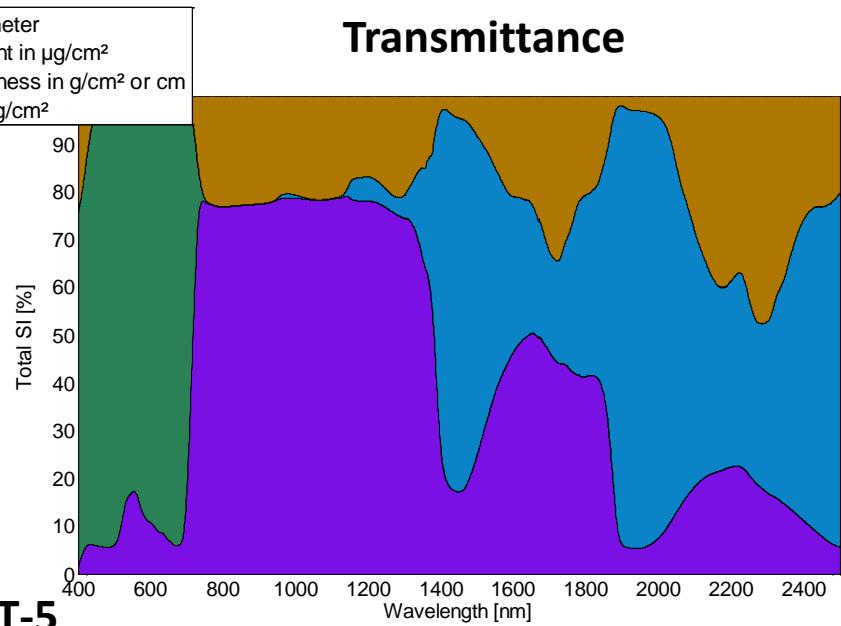
S_{Ti} Leaf: PROSPECT-4/5 (1000#)

PROSPECT-4

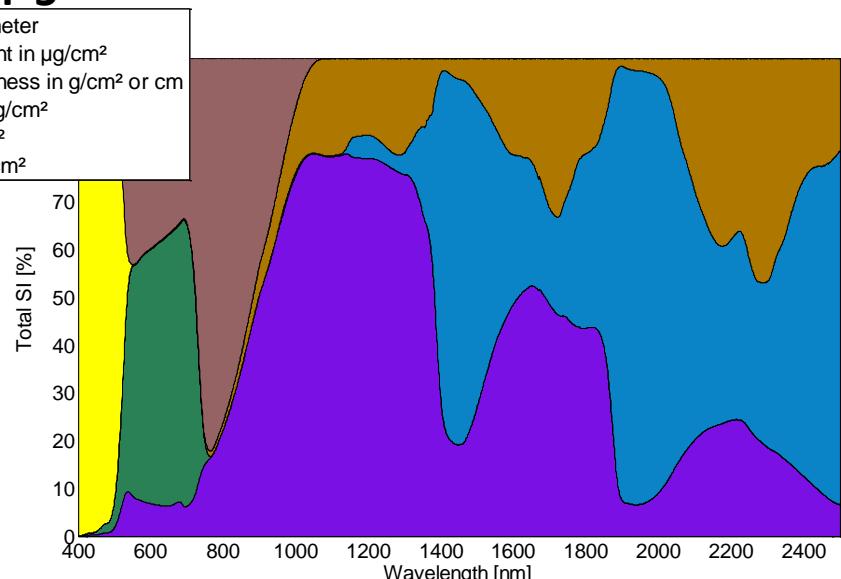
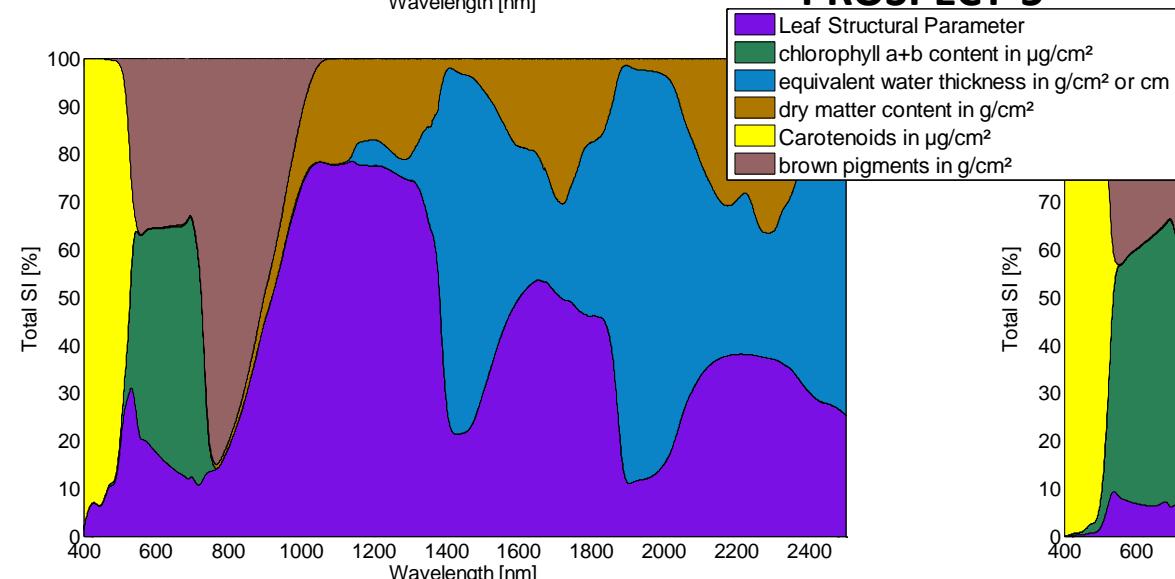
Reflectance



Transmittance



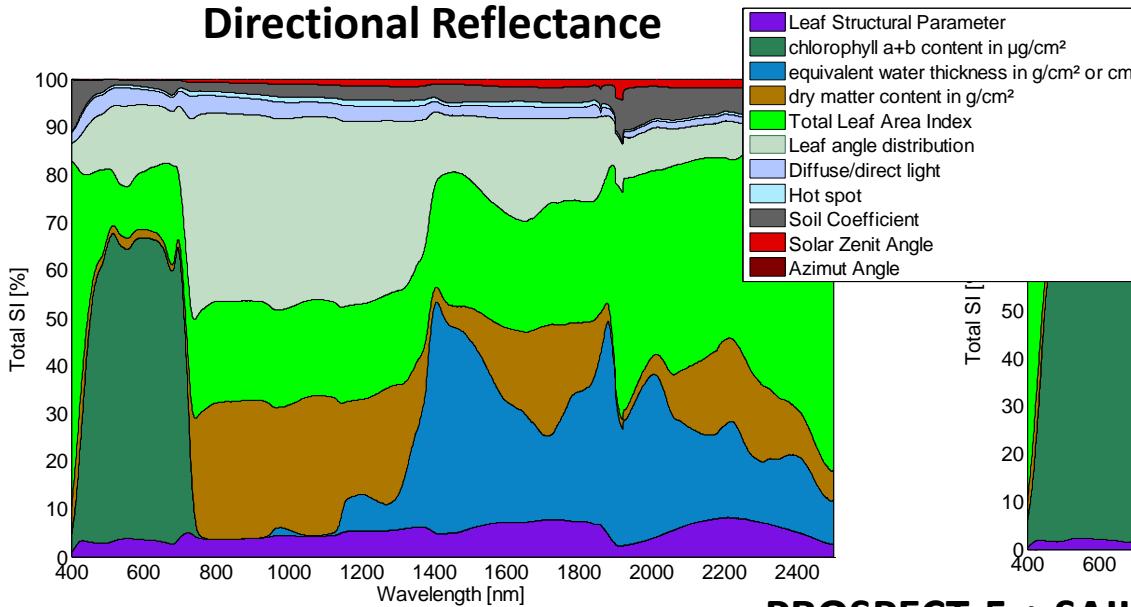
PROSPECT-5



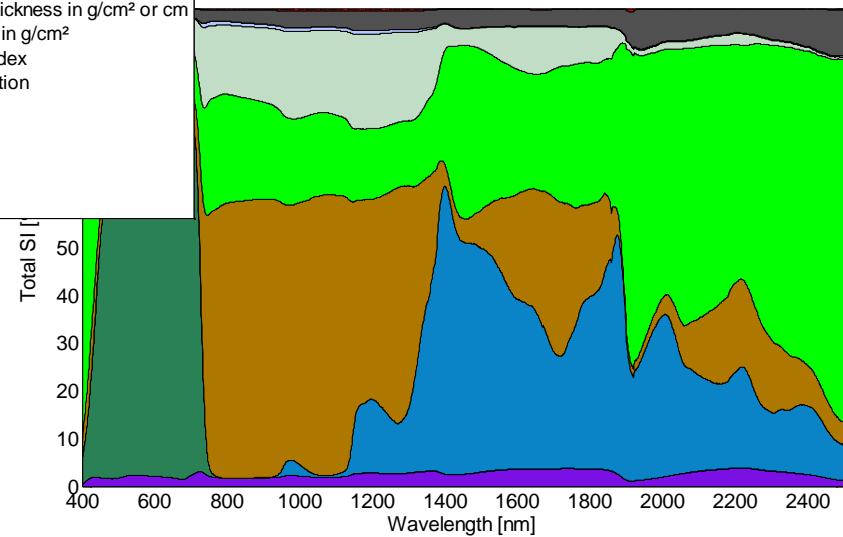
S_{Ti} Canopy: PROSAIL (1000#)

PROSPECT-4 +SAIL

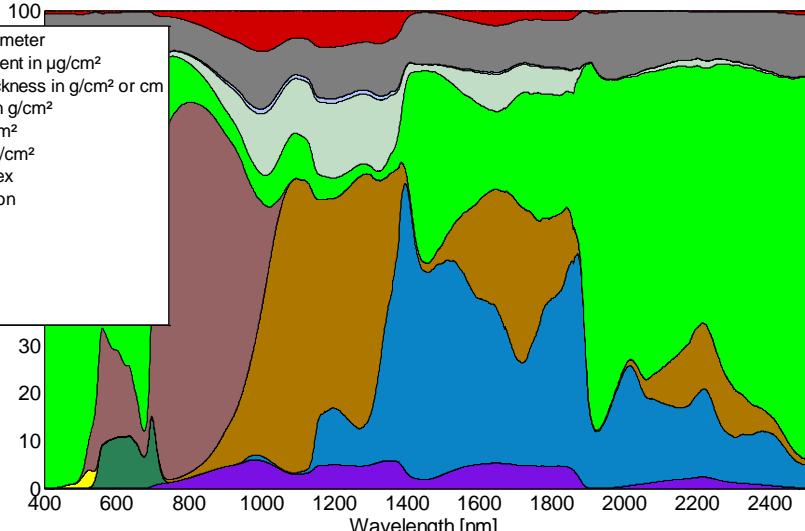
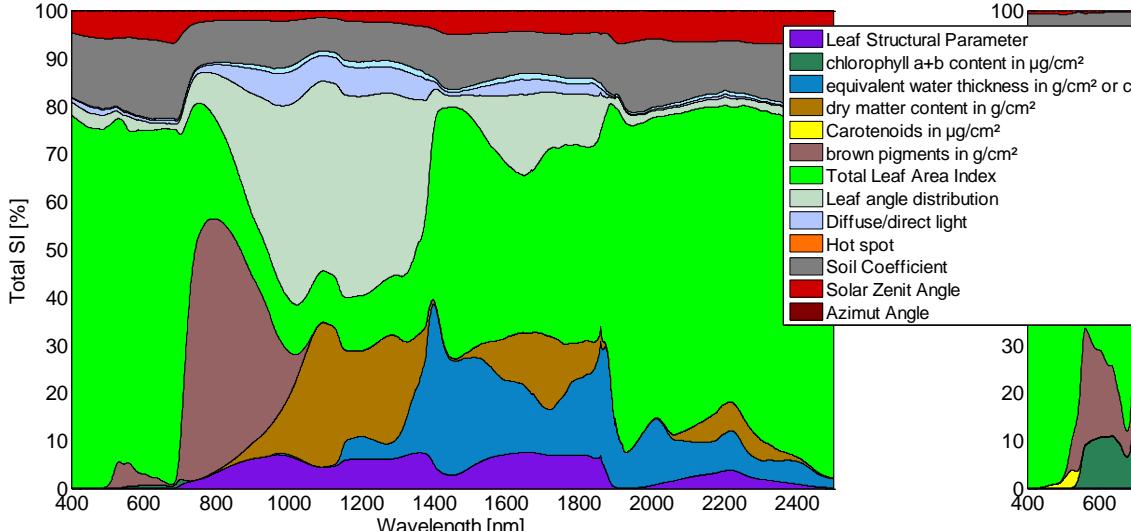
Directional Reflectance



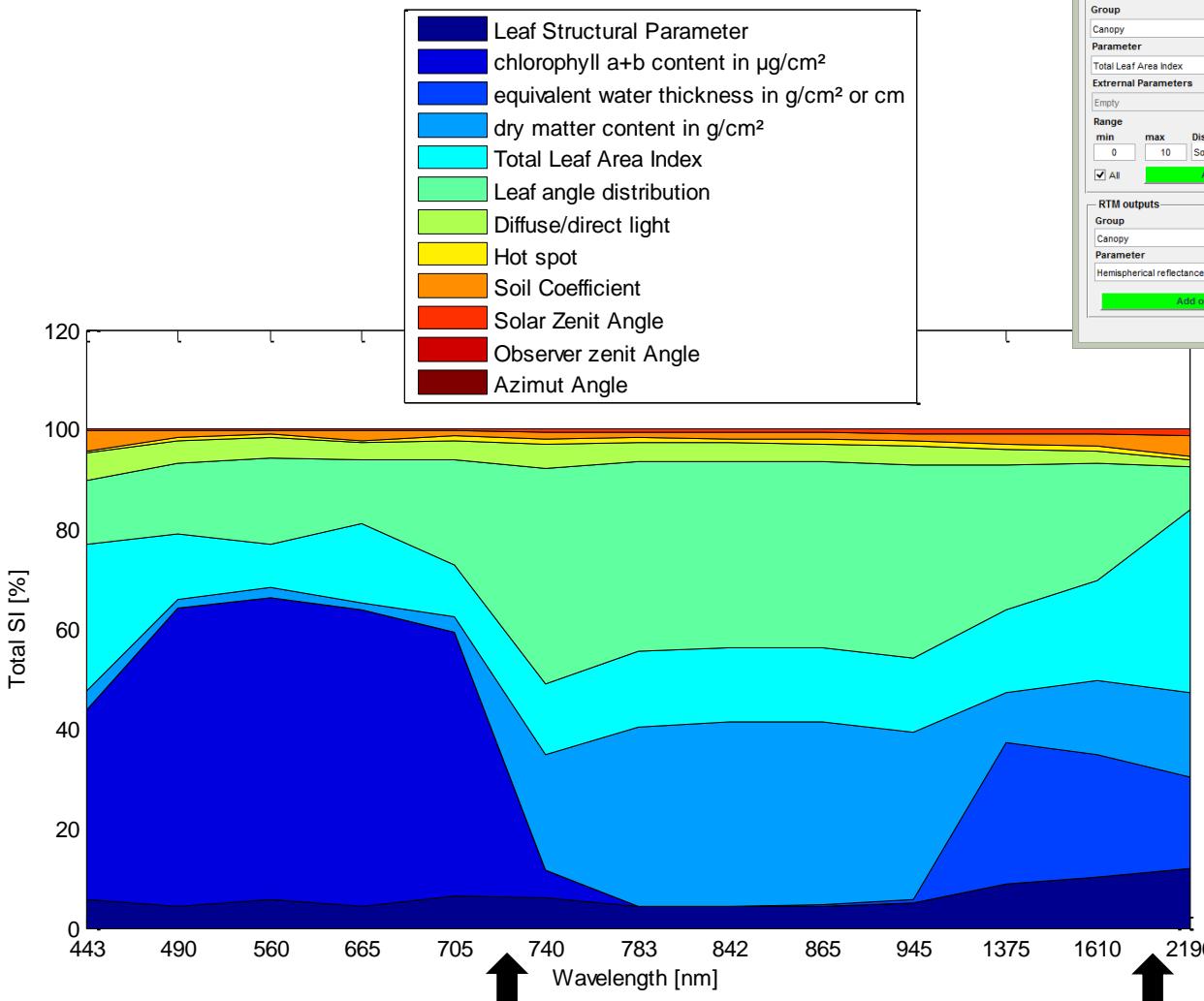
Hemispherical Reflectance



PROSPECT-5 + SAIL



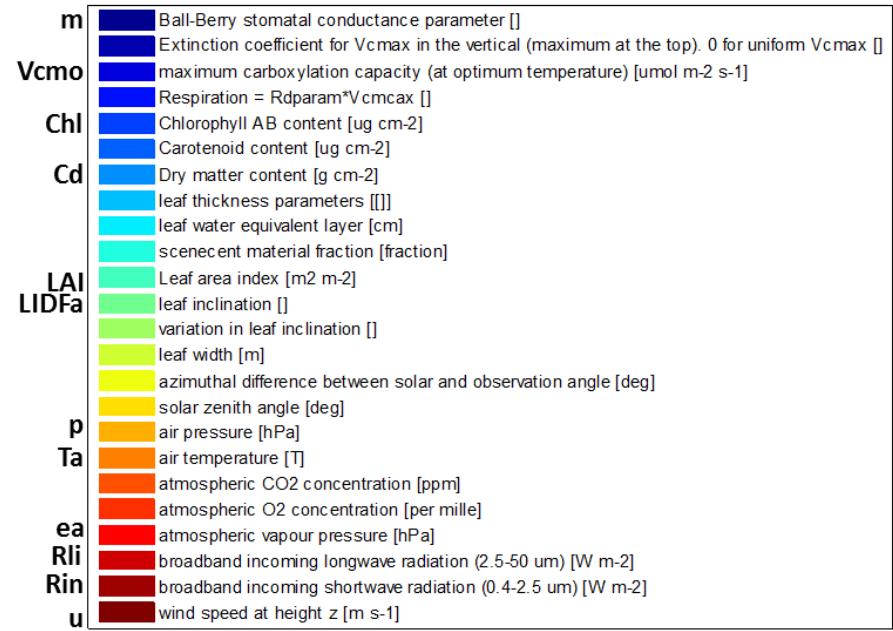
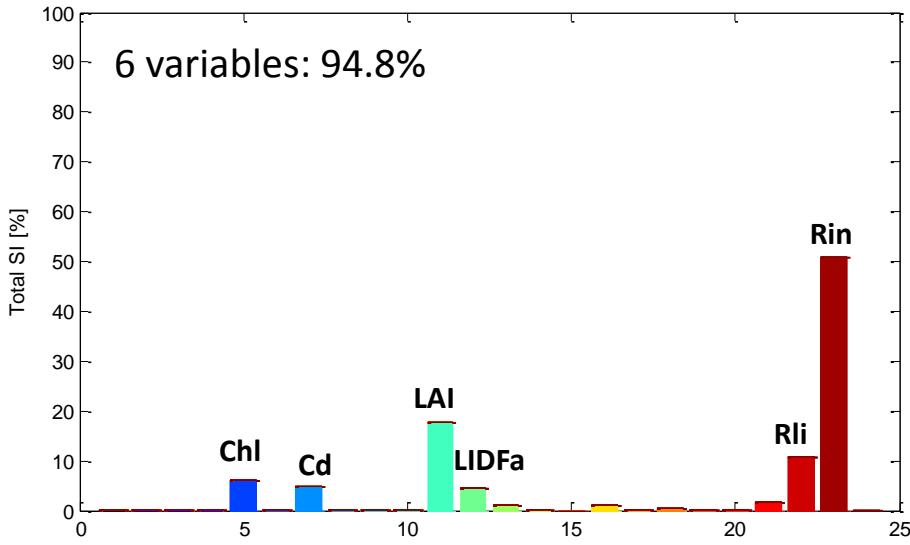
S_{Ti} PROSAIL with Sensor option e.g., Sentinel-2:



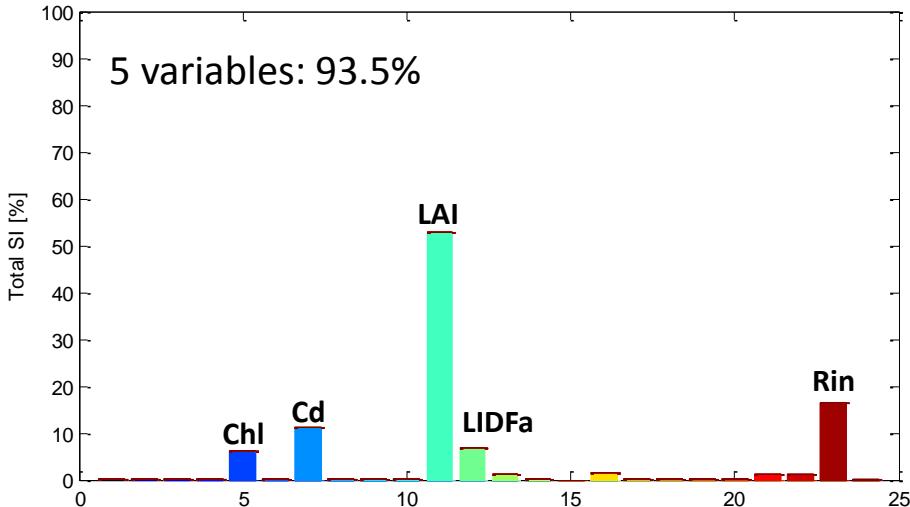
With ARTMO's Sensor module, GSA can be applied to RTMs for any kind of optical sensor (within 400-2400 nm range).

S_{Ti} SCOPE: 25 vars; #1000; Fluxes (1/2)

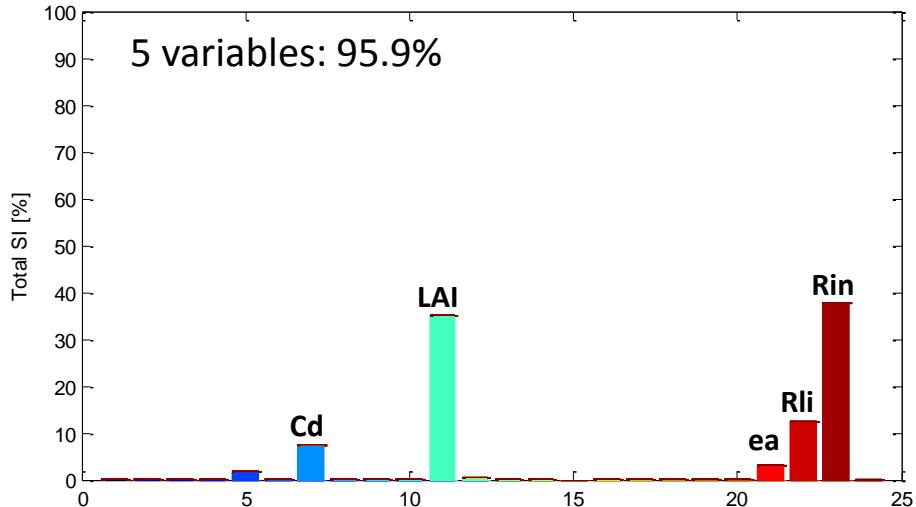
Total net radiation



Net radiation of the soil

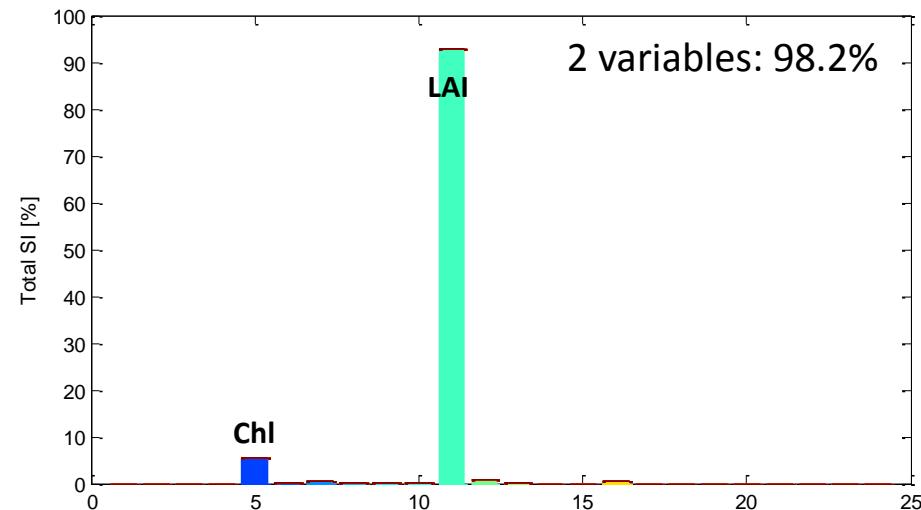


Net radiation of the canopy

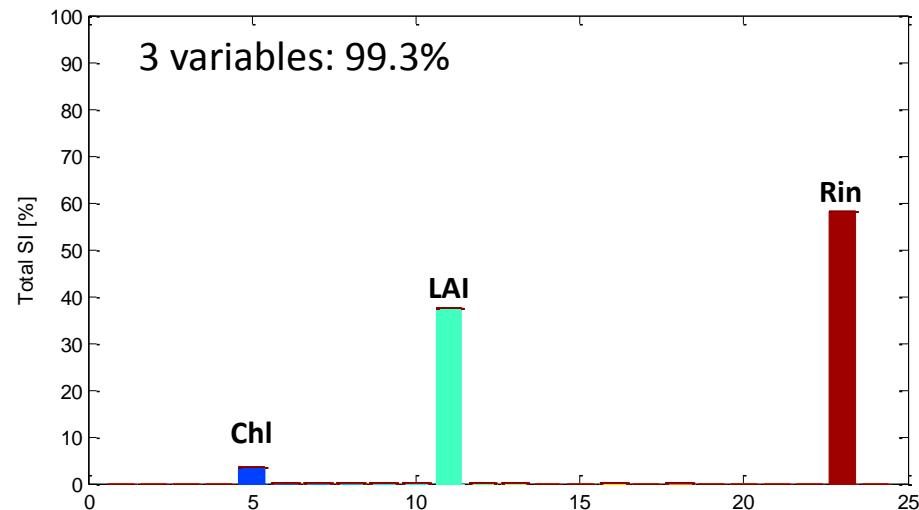


S_{Ti} SCOPE: 25 vars.; #1000; Fluxes (2/2)

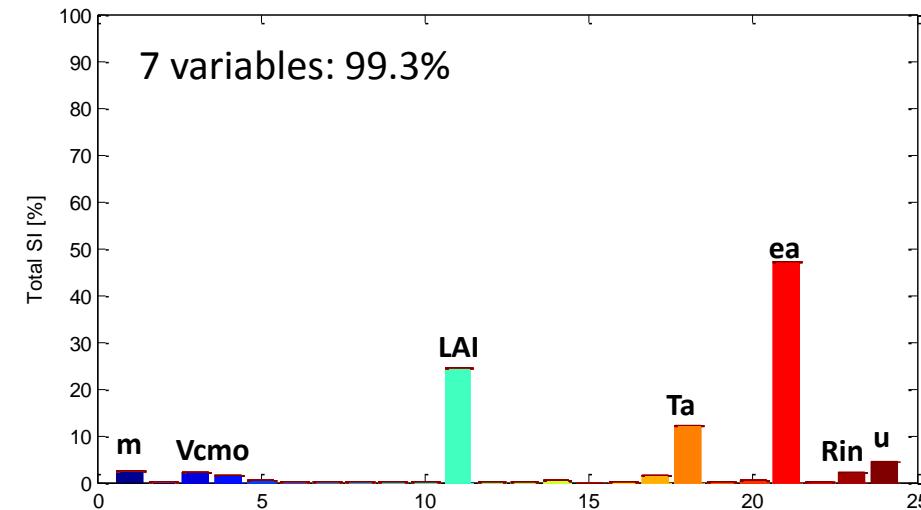
Fraction of absorbed PAR



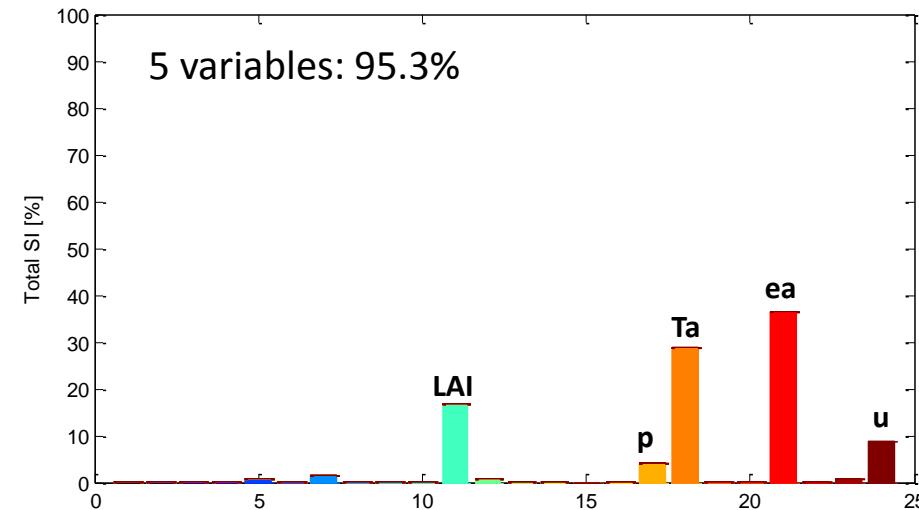
Total absorbed PAR by leaves



Average canopy temperature

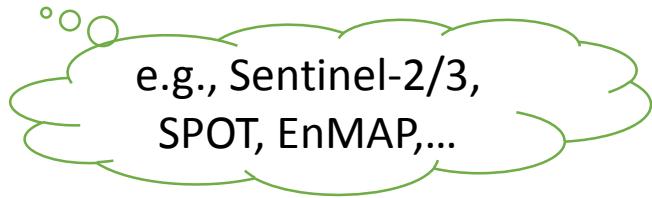


Average soil temperature



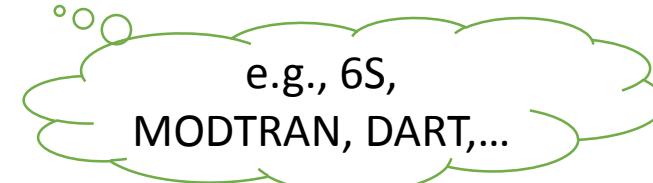
More about GSA SCOPE see Fluorescence session (O10A)

Applications & further development

- GSA useful tool to gain insight into radiative transfer fluxes and model performances, e.g. for a specific sensor setting.

e.g., Sentinel-2/3,
SPOT, EnMAP,...
- GSA enables to configure simplified models for retrieval of specific outputs (e.g. SIF)

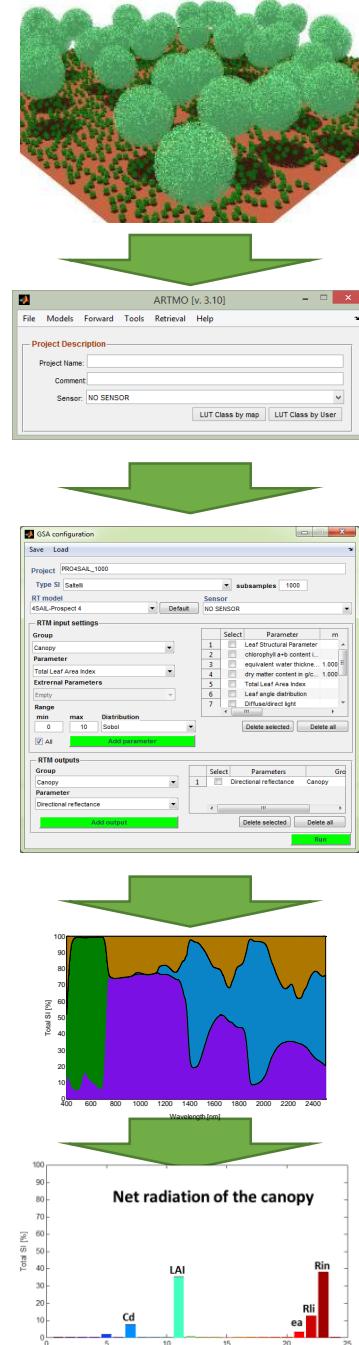
```
graph LR; A[SCOPE] --> B[GSA]; B --> C[SCOPE light]
```

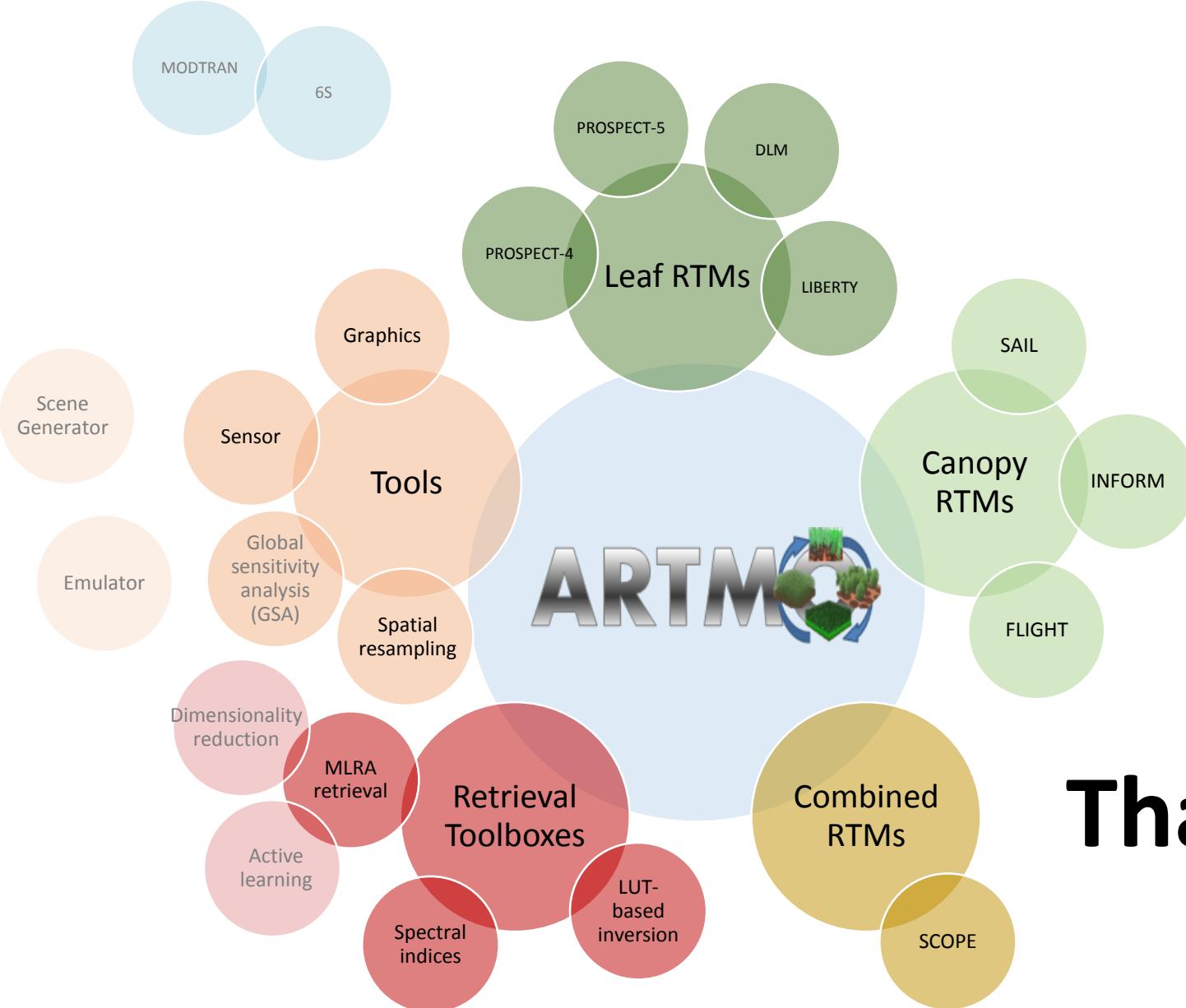
- Further development: GSA of imported data (to analyze models outside the ARTMO framework)

e.g., 6S,
MODTRAN, DART,...

Conclusions

- GSA a useful tool to identify **RTM key and non-influential variables**.
- A new **GSA toolbox** implemented into ARTMO. It calculates Sobol's *first* and *total order sensitivity indices* for a variety of RTMs.
- Depending on the RTM, **not only insight in driving variables along spectral domain, but also of fluxes**.
- GSA toolbox soon publicly available:
<http://ipl.uv.es/artmo/>

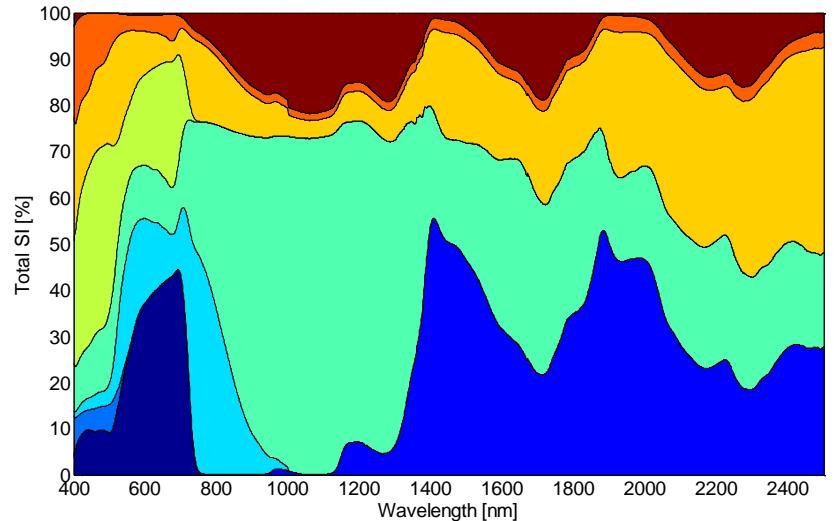




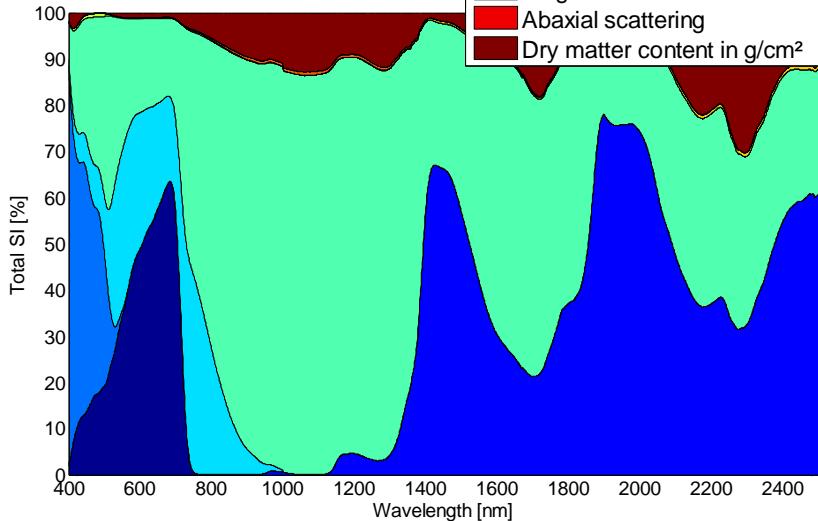
Thanks

<http://ipl.uv.es/artmo/>

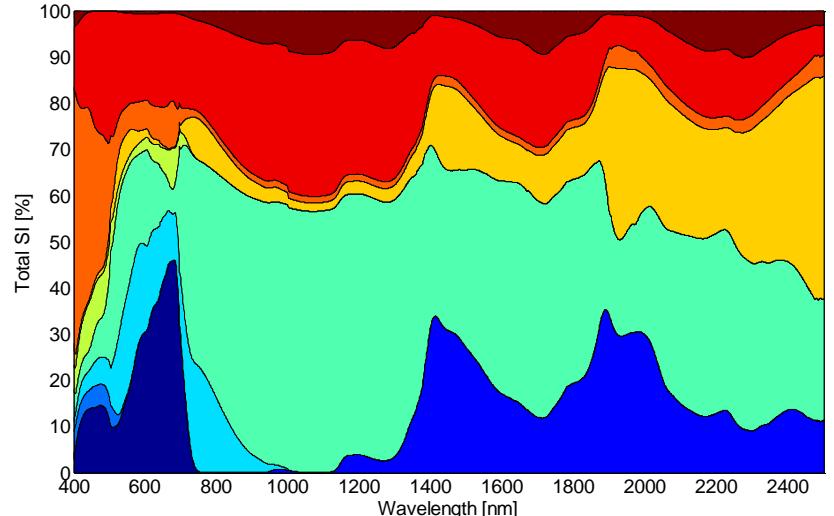
Reflectance of the front leaf



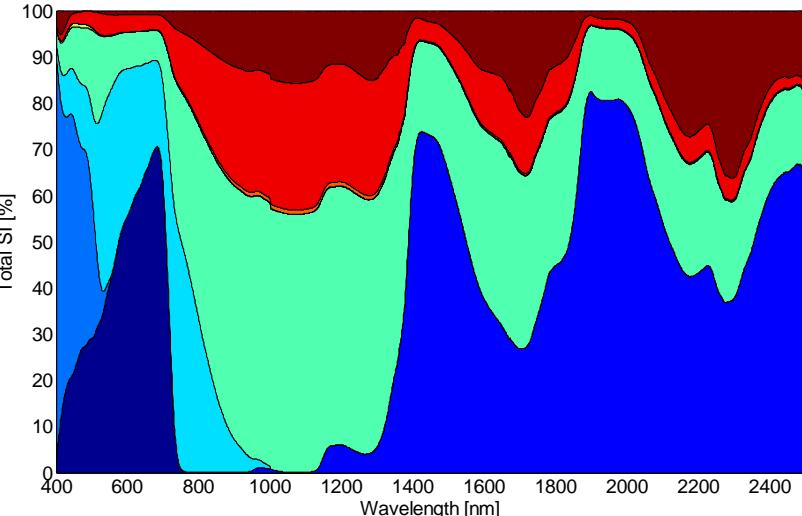
Reflectance of the back leaf



Transmittance of the front leaf

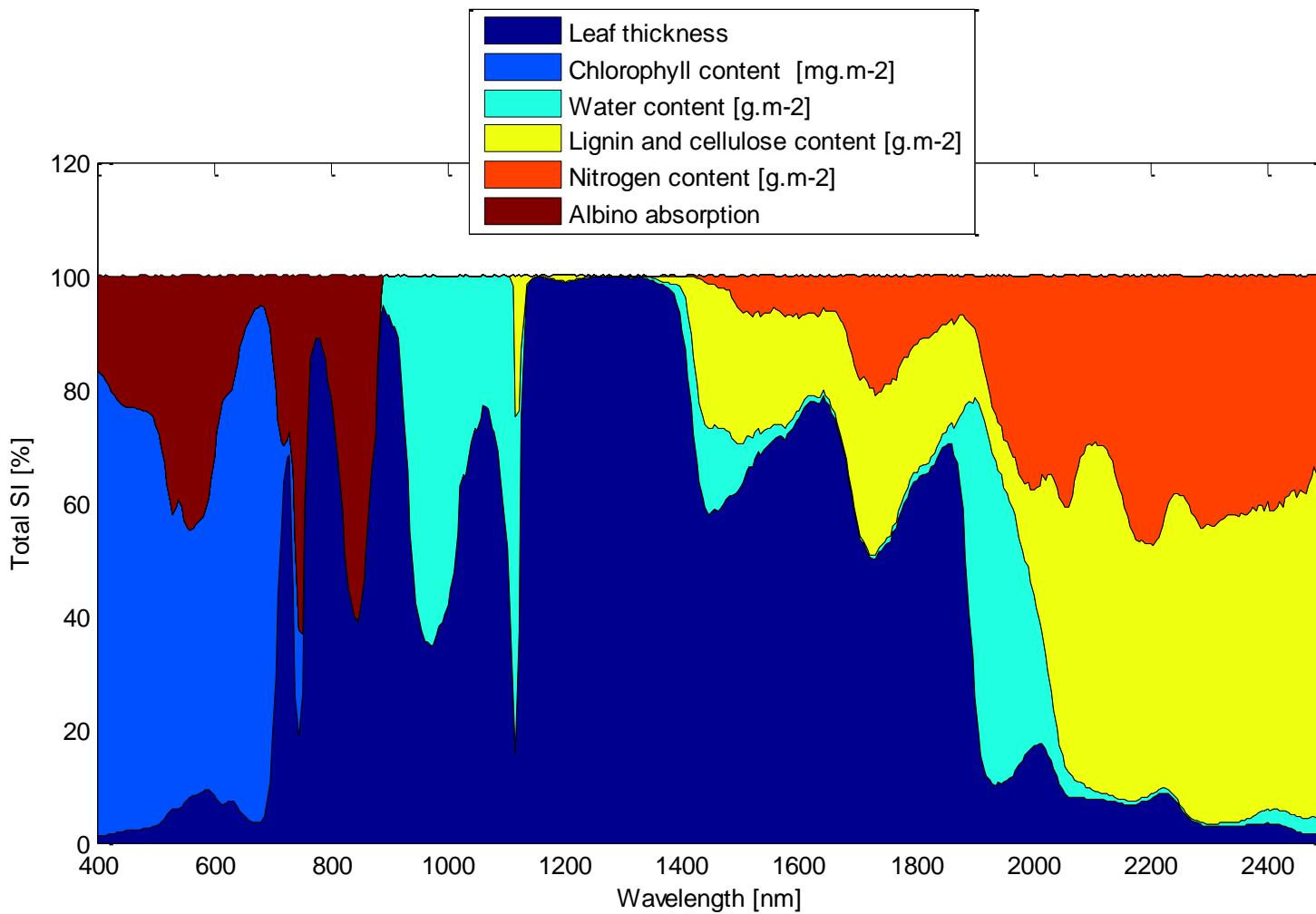


Transmittance of the back leaf



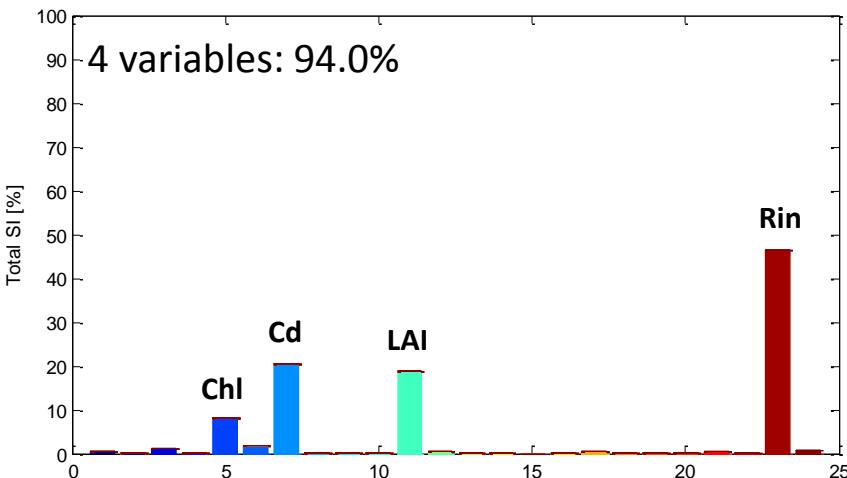
- Chlorophyll a+b content in $\mu\text{g}/\text{cm}^2$
- Equivalent water thickness in $\text{cm}-1$
- Carotenoids a+b content in $\mu\text{g}/\text{cm}^2$
- Brown pigments
- f. air spaces
- f. Pigm. in palisade
- f. total mass in pal.
- roughness factor
- Abaxial scattering
- Dry matter content in g/cm^2

LIBERTY



SCOPE Fluorescence & photosynthesis analysis

Total fluorescence emitted at the top



Net photosynthesis of the canopy

