Application of radiative transfer models to moisture content estimation and burned land mapping

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At a global scale, continents cover ~30% of the Earth surface and vegetation covers ~65% of the continents (forests 24%, prairies and tundra 15%, savannah 15%, crops 11%).

These biomes are crucial for the well-being of humanity. They provide foundations for life on Earth through ecological functions, by regulating the climate and water resources, and by serving as habitats for plants and animals. They also furnish a wide range of essential goods for humans.

Virtually all kinds of vegetation are subject to wildfires: Thus, tropical rain forests that typically do not burn on a large scale were devastated by wildfires during the 1990s...

Wildfires during drought years continue to cause serious impacts to natural resources, public health, transportation and air quality (soot aerosols) over large areas.
One tool: Remote sensing (solar domain, thermal infrared, microwaves). Satellite systems have been used effectively to map active fires and burned areas.
**Question**: How to monitor the evolution of fire risk?

- use of meteorological variables to calculate the water balance → most important factor controlling aboveground primary production, and then fire frequency and intensity.

Water balance

Energy balance
• direct measurement of vegetation water content
  → key factor in assessing flammability and combustibility where a sufficient amount of fuel accumulates.

Fuel Moisture Content

\[ FMC = \frac{fw - dw}{dw} \]

Relative Water Content

\[ RWC = \frac{fw - dw}{tw - dw} \]

Equivalent Water Thickness

\[ EWT = \frac{fw - dw}{A} \]

*FMC* is routinely used by forest services to assess fire danger

*RWC* is directly related to water potential

*EWT* is the hypothetical thickness of a single layer of water
Biochemical composition of leaves

A green-fresh leaf contains:

• water (vacuole): 90-95%
• dry matter (cell walls): 5-10%
  - cellulose: 15-30%
  - hemicellulose: 10-30%
  - proteins: 10-20%
  - lignin: 5-15%
  - starch: 0.2-2.7%
  - sugar
  - etc.
• chlorophyll a and b (chloroplasts)
• other pigments
  - carotenoids
  - anthocyanins, flavons
  - brown pigments
  - etc.

Water seems, at first sight, to be a very simple molecule, consisting of just two hydrogen atoms attached to an oxygen atom.
The molecule of water has three degrees of vibrational and rotational freedom:

- Symmetric stretching mode \( \nu_1 \)
- Bending mode \( \nu_2 \)
- Asymmetric stretching mode \( \nu_3 \)
- Rotational axis A
- Rotational axis B
- Rotational axis C
Transitions between vibrational levels can occur upon absorption of a photon. Sometimes these vibrational absorptions are very localized and can be associated with the stretching or bending of specific bonds.

<table>
<thead>
<tr>
<th>Transition</th>
<th>Absorption intensity</th>
<th>Gas state</th>
<th>Liquid state</th>
<th>Solid state</th>
</tr>
</thead>
<tbody>
<tr>
<td>v1</td>
<td>0.07</td>
<td>2.73 µm 3657 cm$^{-1}$</td>
<td>2.87 µm 3490 cm$^{-1}$</td>
<td>3.05 µm 3277 cm$^{-1}$</td>
</tr>
<tr>
<td>v2</td>
<td>1.47</td>
<td>6.27 µm 1595 cm$^{-1}$</td>
<td>6.08 µm 1645 cm$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>v3</td>
<td>1.00</td>
<td>2.66 µm 3756 cm$^{-1}$</td>
<td>2.90 µm 3450 cm$^{-1}$</td>
<td></td>
</tr>
</tbody>
</table>
Most of the time, however, when two modes lie close in energy, they can mix.

<table>
<thead>
<tr>
<th>Combination</th>
<th>Gas state</th>
<th>Liquid state</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_1 + \nu_3$</td>
<td>0.739 $\mu$m</td>
<td></td>
</tr>
<tr>
<td>$2 \nu_1 + \nu_3$</td>
<td>0.970 $\mu$m</td>
<td>1.004 $\mu$m</td>
</tr>
<tr>
<td>$\nu_1 + \nu_2 + \nu_3$</td>
<td>1.200 $\mu$m</td>
<td>1.272 $\mu$m</td>
</tr>
<tr>
<td>$\nu_1 + \nu_3$</td>
<td>1.450 $\mu$m</td>
<td>1.536 $\mu$m</td>
</tr>
<tr>
<td>$\nu_2 + \nu_3$</td>
<td>1.940 $\mu$m</td>
<td>1.990 $\mu$m</td>
</tr>
</tbody>
</table>

The observed infrared absorptions are combinations of the bending and stretching of several bonds.

Leaf optical properties

Tessa Traeger, 1997, Sight

Reflectance $\rho_f$
Transmittance $\tau_f$
Absorptance $\alpha_f$

\[ \rho_f(\lambda) + \tau_f(\lambda) + \alpha_f(\lambda) = 1 \]
Variations of leaf water content

Fresh and dry poplar (*Populus canadensis*) leaves
Variations of leaf internal structure

corn (*Zea mays*)
sunflower (*Helianthus annuus*)
Plant canopy reflectance

Plant canopy reflectance depends on:
- leaf optical properties
- soil reflectance
- Leaf Area Index
- plant architecture
- etc.

$$R = \frac{E_r}{E_i}$$
Plant canopy reflectance is also a function of:

**Wavelength**

**Viewing angle**

\[ R = R(\lambda, \theta_s, \theta_v, \phi_v) \]

**Question:** How to estimate vegetation water content from measurements of reflectance?
Semi-empirical models

- Correlation between leaf water status and simple wavebands or combination of wavebands

\[ C_w = f(\rho(\lambda_1), \ldots, \rho(\lambda_n)) \]

At the leaf level

- Aoki et al. (1988)
  \[ EWT = \alpha \frac{\rho_{1650}}{\rho_{1430}} + \beta \]

- Ceccato et al. (2001)
  \[ RWC = f\left(\frac{\rho_{1600}}{\rho_{820}}\right) = f(MSI) \]

- Inoue et al. (1993)
  \[ EWT = \alpha \frac{\rho_{1200}}{\rho_{1430}} + \beta \]

- Peñuelas et al. (1993)
  \[ EWT = \alpha \frac{\rho_{970}}{\rho_{900}} + \beta = \alpha WI + \beta \]

  \[ RWC = LWCI = \frac{-\ln(1 - (\rho_{820} - \rho_{1600}))}{-\ln(1 - (\rho_{820} - \rho_{1600}^{ET}))} \]
At the canopy level

Normalized Difference Water Index
\[
NDWI = \frac{R_{860} - R_{1240}}{R_{860} + R_{1240}}
\]

Gao (1996)

Water Band Index
\[
WBI = \frac{R_{900}}{R_{970}}
\]

Gamon et al. (1999)

Canopy Structure Index
\[
CSI = 2sSR - sSR^2 + sWI^2
\]
\[
sSR = \frac{1}{20} \left( \frac{R_{800}}{R_{680}} - 1 \right)
\]
\[
sWI = \frac{1}{0.8} \left( \frac{R_{900}}{R_{1180}} - 1 \right)
\]

Sims and Gamon (2003)

Relative Depth Index
\[
RDI = 100 \times \frac{R_{1116} - R_{\text{min}}}{R_{1116}}
\]

with \( R_{\text{min}} = \min \{ R_{1120} \rightarrow R_{1250} \} \)

Rollin and Milton (1998)

Modified Normalized Difference Water Index
\[
mNDWI = \frac{R_{1070} - R_{1200}}{R_{1070} + R_{1200}}
\]

Roberts et al. (2003)
• Multiple stepwise regression analysis

\[ C_w = \sum_{i=1}^{n} \alpha_i \rho(\lambda_i) \]

• Spectral mixture analysis

\[ R(\lambda) = (a + b \lambda) \exp\left( -\sum_{i=1}^{n} k_i(\lambda) C_i \right) \]

Spectral fitting of liquid water absorption during atmospheric calibration procedure

Radiative transfer models

Why use models?

• Increase our understanding of how electromagnetic radiation interacts with the elements comprising terrestrial ecosystems → sensitivity analyses: direct mode
• Relate remote sensing observables to fundamental biophysical attributes → model optimization: inverse mode
• Understand the scaling properties of observable electromagnetic features and responses
• Develop correction techniques to handle the variable nature of sensor data

R. Myneni, 1995
## Leaf optical properties models

<table>
<thead>
<tr>
<th>Plate models</th>
<th>PROSPECT</th>
<th>leaf structure parameter</th>
<th>( \rho(\lambda), \tau(\lambda), \varphi(\lambda) )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>- leaf structure parameter</td>
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<td></td>
<td></td>
<td>- biochemical content</td>
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<tr>
<td>N-flux models</td>
<td>K-M</td>
<td>- scattering coefficient</td>
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<td>- biochemical content</td>
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<tr>
<td>Radiative transfer</td>
<td>LEAFMOD</td>
<td>- cell diameter</td>
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<tr>
<td>equation</td>
<td></td>
<td>- leaf thickness</td>
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<td>- intercellular air spaces</td>
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<tr>
<td>Compact spherical</td>
<td>LIBERTY</td>
<td>- cell diameter</td>
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<td>particle models</td>
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<td>- leaf thickness</td>
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<td>( \rho(\lambda), \tau(\lambda) )</td>
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<tr>
<td>Stochastic models</td>
<td>LFMOD1, SLOP</td>
<td>- probabilities of scattering</td>
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<td>and absorption</td>
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<td>- biochemical content</td>
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<td></td>
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<td>( \rho(\lambda), \tau(\lambda), \varphi(\lambda) )</td>
<td></td>
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<tr>
<td>Ray tracing models</td>
<td>RAYTRTRAN, ABM</td>
<td>- description of the leaf</td>
<td></td>
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<td>internal structure in three</td>
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<td>dimensions</td>
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<td></td>
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<td>- biochemical content</td>
<td></td>
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<td></td>
<td></td>
<td>( \rho(\lambda, \theta), \tau(\lambda, \theta) )</td>
<td></td>
</tr>
</tbody>
</table>
Specific absorption coefficient of constituent $i$: $k_i(\lambda)$

\[
k(\lambda) = \sum k_i(\lambda) \times C_i
\]

\[
T(\lambda) = \exp(-k(\lambda) \times d)
\]


Real refractive index of constituent $i$: $n_i(\lambda)$

\[ n_1 \times \sin \theta_1 = n_2 \times \sin \theta_2 \]


The PROSPECT model

Monocots

Dicots

plate model

N layers model


leaf structure parameter
chlorophyll $a+b$ concentration ($\mu$g.cm$^{-2}$)
equivalent water thickness (cm)
dry matter content (g.cm$^{-2}$)

$N = 1.5, C_{ab} = 50 \ \mu$g.cm$^{-2}, C_m = 0.005 \ \text{g.cm}^{-2}$
Spectral sensitivity analysis of PROSPECT with the design of numerical experiments method → matrix model

\[
[\rho(\lambda), \tau(\lambda)] = N + C_{ab} + C_w + C_m + N C_{ab} + N C_w + N C_m + C_{ab} C_w + C_{ab} C_m + C_w C_m
\]

\(C_{ab} = 50 \mu\text{g.cm}^{-2}, C_w = 0.0110 \ \text{cm}, C_m = 0.005 \ \text{g.cm}^{-2}\)

\(N = 1.5, C_{ab} = 50 \mu\text{g.cm}^{-2}, C_w = 0.0110 \ \text{cm}\)
Effect of $C_w$ on leaf reflectance computed with PROSPECT
Contribution of N, $C_{ab}$, $C_w$, and $C_m$ on leaf reflectance computed with PROSPECT
## Canopy reflectance models

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Models</th>
<th>Parameters</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parametric models</td>
<td>LiSK, RPV</td>
<td>- albedo&lt;br&gt;- shape of the radiation field</td>
<td>$R(\lambda, \theta)$</td>
</tr>
<tr>
<td>N-flux models</td>
<td>LAM, SAIL, K-M</td>
<td>- leaf optical properties&lt;br&gt;- canopy architecture&lt;br&gt;- soil optical properties</td>
<td>$R(\lambda, \theta), F(\lambda)$</td>
</tr>
<tr>
<td>Radiative transfer equation</td>
<td>LCM2, NADIM, N-K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geometrical models</td>
<td>SLS</td>
<td>- leaf optical properties&lt;br&gt;- description of the canopy architecture in three dimensions&lt;br&gt;- soil optical properties</td>
<td>$R(\lambda, \theta)$</td>
</tr>
<tr>
<td>Hybrid models</td>
<td>DART, GORT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiosity and ray tracing models</td>
<td>RAYTRAN, FLIGHT, SPRINT, RGM</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Scaling-up to the satellite level

Radiative transfer models
- 5S, 6S, LOWTRAN, MODTRAN
- canopy reflectance
- horizontal visibility
- model of atmosphere
- aerosol model

\[ R^*(\lambda, \theta) \]
Use of radiative transfer models to simulate plant canopy spectral and bidirectional reflectance.
Bidirectional sensitivity of PROSPECT+SAIL (PROSAIL) with the design of numerical experiments method:

- Sun zenith angle: $\theta_s = 30^\circ$
- canopy observed under several viewing angles $\theta_v$

Equivalent water thickness $C_w$
Leaf area index LAI
Leaf inclination angle $\theta_l$


Designing spectral indices to estimate vegetation water content: The Global Vegetation Moisture Index (GVMI)

(1) rectification of the NIR band to avoid atmospheric and angular effects
(2) combination with the SWIR band to generate an optimal index formulae

\[ GVMI = \frac{(NIR_{\text{rect}} + 0.1) - (SWIR + 0.02)}{(NIR_{\text{rect}} + 0.1) + (SWIR + 0.02)} \]

Simulations with PROSPECT + NADIM + 6S

\[ GVMI = 1.53 - \frac{1.4}{1 + 0.000517 \times EWT_{\text{canopy}}} - 0.000099 \times EWT_{\text{canopy}} \]

Inversion of canopy reflectance models

The inversion procedure consists in retrieving the unknown parameter vector $\Theta$ by minimizing the non-linear least-squares function $\chi^2$:

$$\chi^2 = \sum_{i=1}^{n} \left( \rho_i - M(\Theta, X_i) \right)^2$$

A successful inversion is the conjunction of three factors:

- calibrated data
- minimization of the merit function
- a good model

- an appropriate inversion procedure
  - iterative algorithm
  - neural networks
  - look-up tables
• Retrieval of water content at the leaf level

\[ \chi^2 = \sum_{i=1}^{n} \left( \rho_i - \rho_{\text{mod}}(\Theta, \lambda) \right)^2 + \left( \tau_i - \tau_{\text{mod}}(\Theta, \lambda) \right)^2 \]

<table>
<thead>
<tr>
<th>Model</th>
<th>Parameter</th>
<th>$R^2$</th>
<th>RMSE (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROSPECT</td>
<td></td>
<td>×</td>
<td>0.0025</td>
</tr>
<tr>
<td>Baret and Fourty (1997)</td>
<td>$EWT$</td>
<td>0.95</td>
<td>0.0018</td>
</tr>
<tr>
<td>Jacquemoud et al. (2000)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Newnham and Burt (2001)</td>
<td></td>
<td>0.93</td>
<td>×</td>
</tr>
<tr>
<td>LIBERTY</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dawson et al. (1998)</td>
<td>$FMC$</td>
<td>0.86</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Water loss:

- Baret and Fourty (1997): 0.95, 0.0018 cm
- Jacquemoud et al. (2000): 0.93
- Newnham and Burt (2001): 0.86, 1.3

- LIBERTY
  - Dawson et al. (1998): 0.86, 1.3

Graphs showing estimated vs. measured values.
• Retrieval of water content at the canopy level

\[ \chi^2 = \sum_{i=1}^{n} \left( R_i - R_{\text{mod}}(\Theta, \lambda) \right)^2 \]

**Step 1**
spectral unmixing

**Step 2**
inversion of the K-M model on the 1.55-1.75 μm region

Simple Ratio Water Index

\[
SRWI = \frac{R_{860}}{R_{1240}}
\]

Time series of MODIS-estimated leaf \( C_w \) in the study region of chaparral vegetation used for ground truth data collection for the period June–September 2000 (Julian days 161, 169, 185, 201, 233, 241, 249, 265, and 273).

CONCLUSION

• The use of radiative transfer models to estimate vegetation moisture content is still in its infancy

• Operational mapping will require more theoretical and field work:
  - at the leaf level
  - at the canopy level → inversion procedures, validation campaigns
• The use of other canopy biophysical characteristics might be useful to assess fire risk → canopy architecture, brown pigments, etc.

• The spectral and bidirectional properties of burnt areas are still unknown → laboratory measurements

The modeling of these properties is emerging → fitting of parametric models (Lajas et al., 2001; Roy et al., 2003)