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RETRIEVAL OF LEAF AND DRY MATTER CONTENTS USING RADIATIVE TRANSFER MODELING AND NIR IMAGING SPECTROSCOPY

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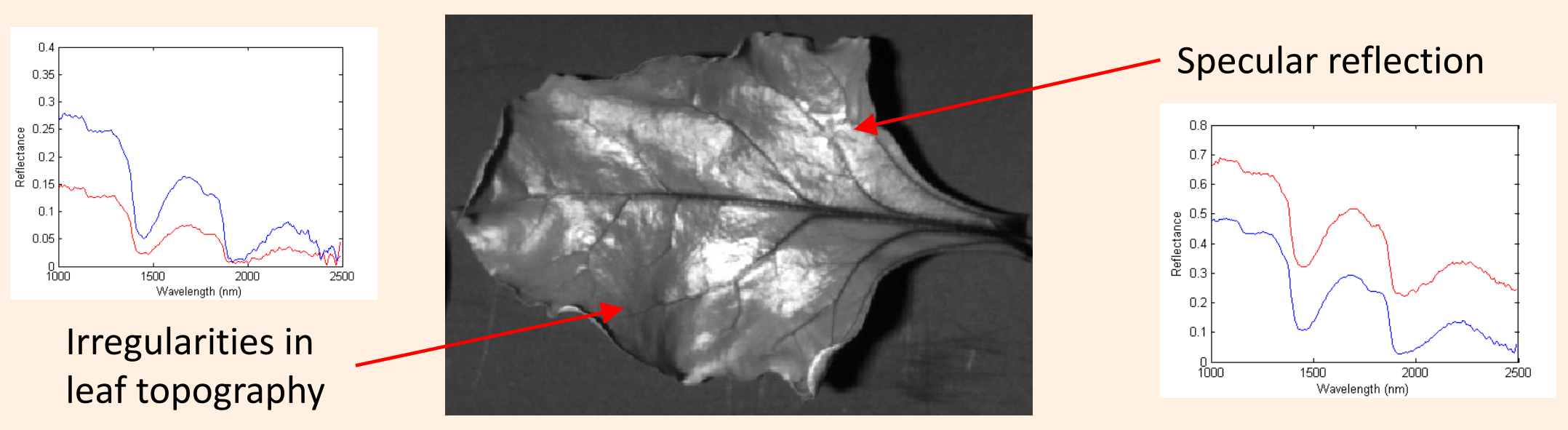
Context

- **Imaging spectroscopy,** a powerful tool for spatially characterizing vegetation:
  - ✓ Identification of plant pigments (*Blackburn, 2007*),
  - ✓ Detection of freezing stress (*Nicotra et al, 2004*),
  - ✓ Detection of leaf diseases (*Malhein et al, 2013*)…
- **The NIR/SWIR range** (1000-2500 nm), a relevant spectral range for retrieving leaf water content and dry matter content (strong absorption/scattering features).

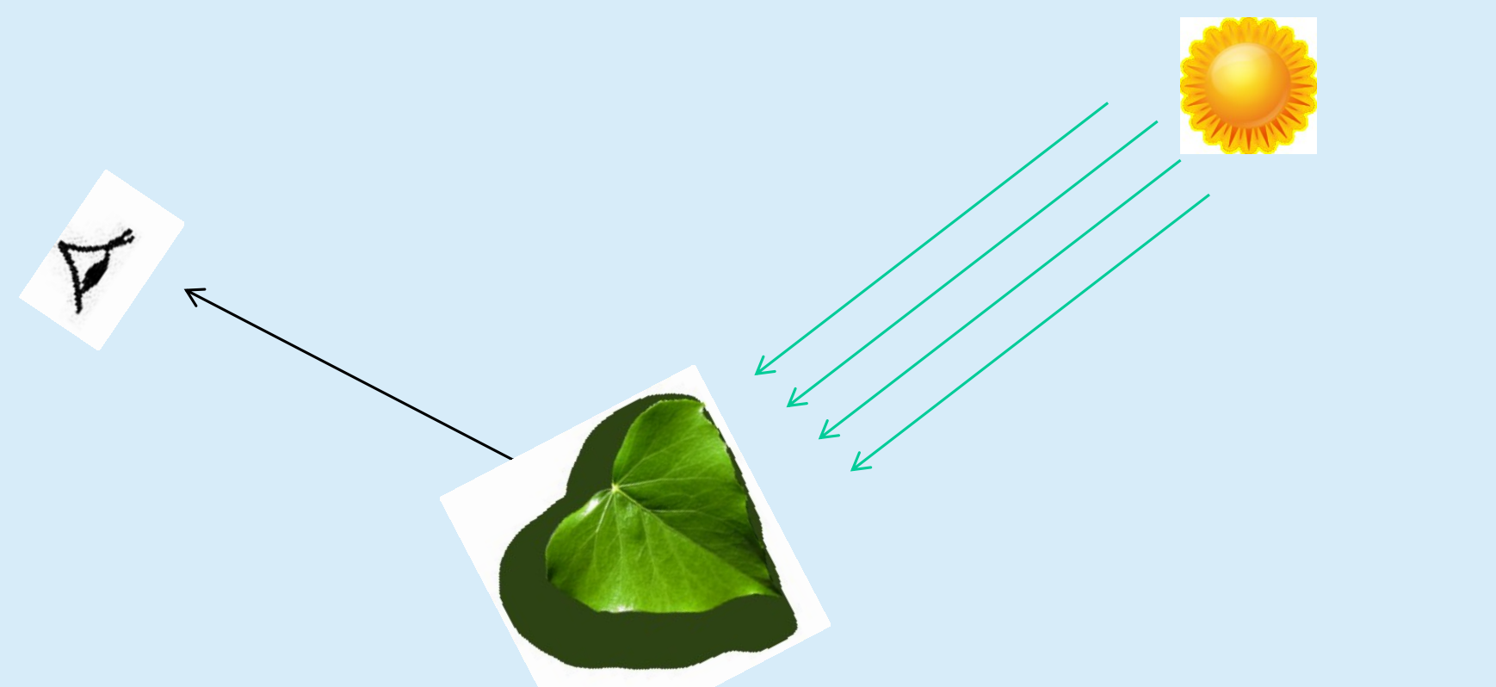
- **Usual methods for retrieving leaf parameters are based either on**
  - ✓ the targeted biochemical variables (statistically-based methods, machine learning algorithms),
  - ✓ the radiometric measurement (physically-based methods through the inversion of radiative transfer models)
- **No radiative transfer models available for close-range imaging spectroscopy !**

- **Objective:** Develop a leaf radiative transfer model for close-range imaging spectroscopy by adapting an existing leaf directional-hemispherical reflectance model.



Theory – The COSINE model

- **Hypothesis:** a close bidirectional approximation can be obtained under specific experimental and instrumental lab conditions, i.e.,
  - ✓ Collimated light beam,
  - ✓ Small sensor FOV (imaging spectroscopy: ok)



- **What physical quantity is retrieved at the pixel level ?**
  - ✓ Hyperspectral measurement → Bidirectional Reflectance Factor (BRF) ?

$$R(\theta_s;\theta_v,\varphi_v) \approx \frac{L_r(\theta_s;\theta_v,\varphi_v)}{L_r^{id}(\theta_s)}$$

Radiance measured on the leaf

Radiance measured on the reference surface

  - ✓ More realistically: hyperspectral measurement → pseudo-BRF

$$R_{hsi}(\theta_s,\theta_i;\theta_v,\varphi_v) \approx \frac{L_r(\theta_i;\theta_v,\varphi_v)}{L_r^{id}(\theta_s)}$$

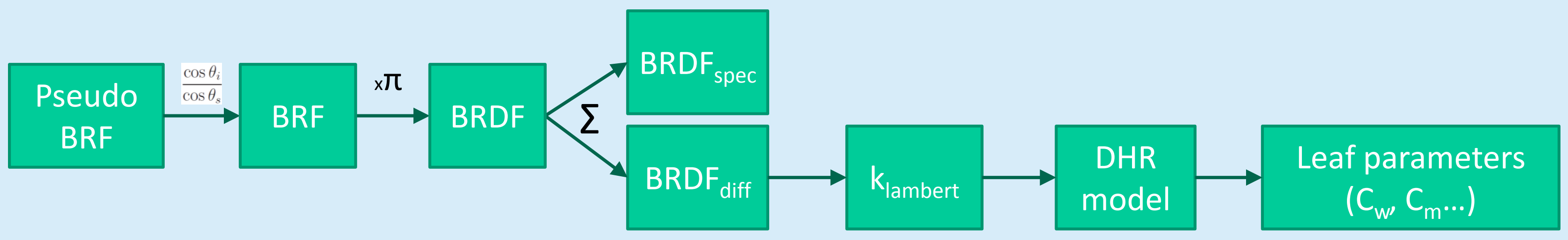
Light incident angle = f (illumination angle, leaf topography)

Illumination zenith angle

  - ✓ It can be shown that

$$R_{hsi}(\theta_s,\theta_i;\theta_v,\varphi_v) \approx R(\theta_i;\theta_v,\varphi_v)\frac{\cos\theta_i}{\cos\theta_s} = R(\theta_i;\theta_v,\varphi_v) \text{ if } \theta_i = \theta_s$$

- **How to model the leaf BRF as a function of leaf optical properties?**
  - ✓ Proposed approach: relate the leaf BRF to an existing leaf DHR model such as PROSPECT (*Jacquemoud & Baret, 1990*) or LIBERTY (*Dawson et al, 1998*).



  - ✓ The COSINE model (ClOse-range Spectral Imaging of lEaves)

$$\widetilde{R_{hsi}}(\theta_s,\theta_i;\boldsymbol{\vartheta}_{dhr},b_{spec}) = \left(\frac{\cos\theta_i}{\cos\theta_s}\right)\left[\widetilde{\rho}(\boldsymbol{\vartheta}_{dhr}) + b_{spec}\right]$$

    - ➢ One known parameter (θ_s)
    - ➢ (N_{dhr}+2) unknown parameters ($\boldsymbol{\vartheta}_{dhr}, b_{spec}, \theta_i$)

Materials & Methods

- **Data set**
  - ✓ 5 plant species (laurel, ivy, bamboo, laurestine, holly) + sugar beet,
  - ✓ For each leaf, 3 average incident angles (30˚, 10˚, 50˚),
  - ✓ Spectral range : 1000-2500 nm
  - ✓ Spatial resolution: 0.23 mm,
  - ✓ Destructive measurements of water content (C_w) and dry matter content (C_m)

Parameter	Number of samples	Mean	Min/Max	Standard deviation
C_w [cm]	22	0.0104	0.0049/0.0164	0.0040
C_m [g.cm^{-2}]	22	0.0091	0.0052/0.0129	0.0023

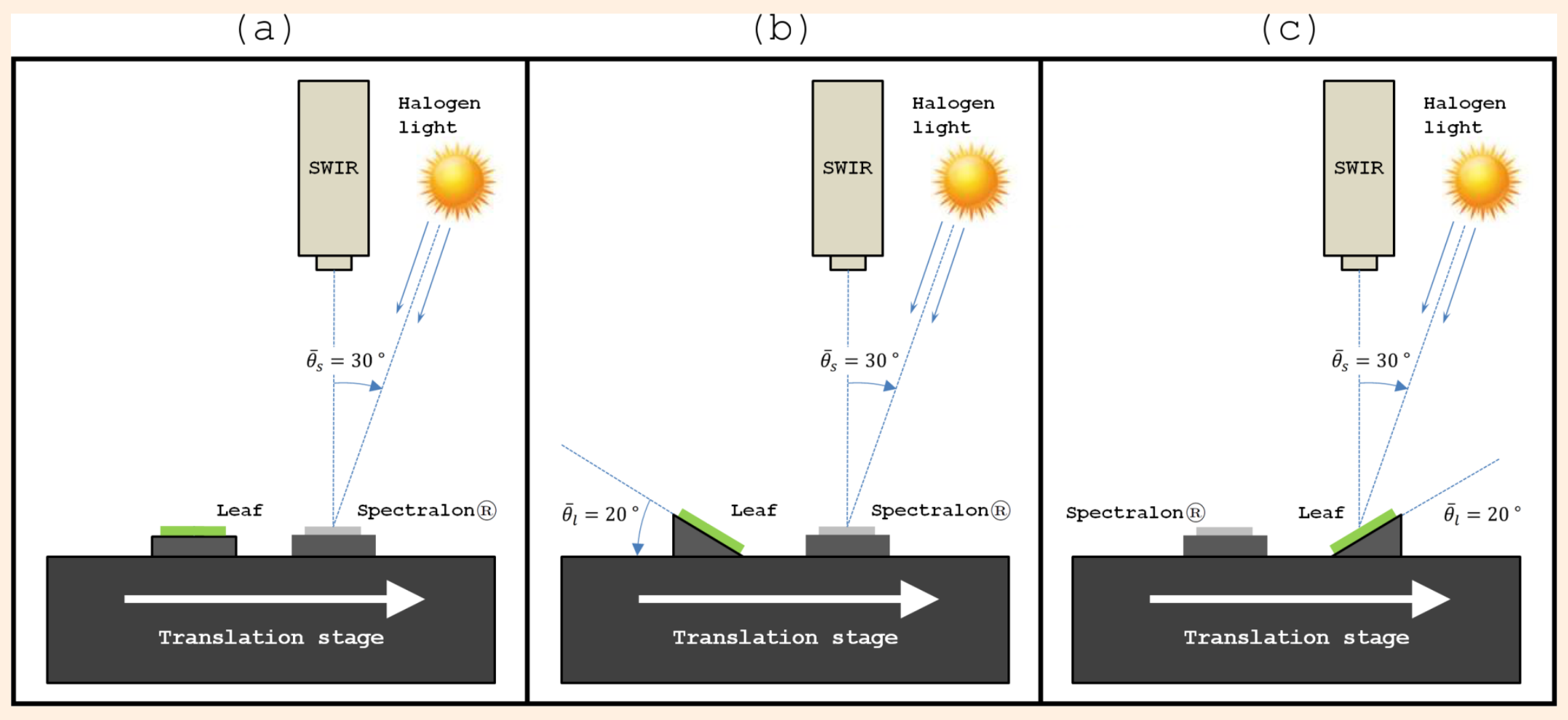


Figure: *Three acquisition configurations for each leaf : (a) $\bar{\theta}_i$ = 30˚, (b) $\bar{\theta}_i$ = 10˚ and (c) $\bar{\theta}_i$ = 50˚.*

- **Retrieval of leaf parameters**
  - ✓ Considered leaf DHR model : PROSPECT 5b (*Féret et al, 2008*)
  - ✓ In the 1000-2500 nm range:
    - ➢ $\tilde{\rho}_{PROSPECT} = \tilde{\rho}_{PROSPECT}(\boldsymbol{\vartheta}_{dhr})$ avec $\boldsymbol{\vartheta}_{dhr}=(N,C_w,C_m)$
  - ✓ Combined PROSPECT+COSINE=PROCOSINE model:
    - ➢ $\widetilde{R}_{hsi,PROCOSINE} = \widetilde{R}_{hsi,PROCOSINE}(\boldsymbol{\vartheta})$ avec $\boldsymbol{\vartheta}=(N,C_w,C_m,b_{spec},\theta_i)$
  - ✓ Model inversion based on iterative optimization of a merit function relating the measured and simulated spectra (3 parameters for PROSPECT, 5 parameters for PROCOSINE)

Results

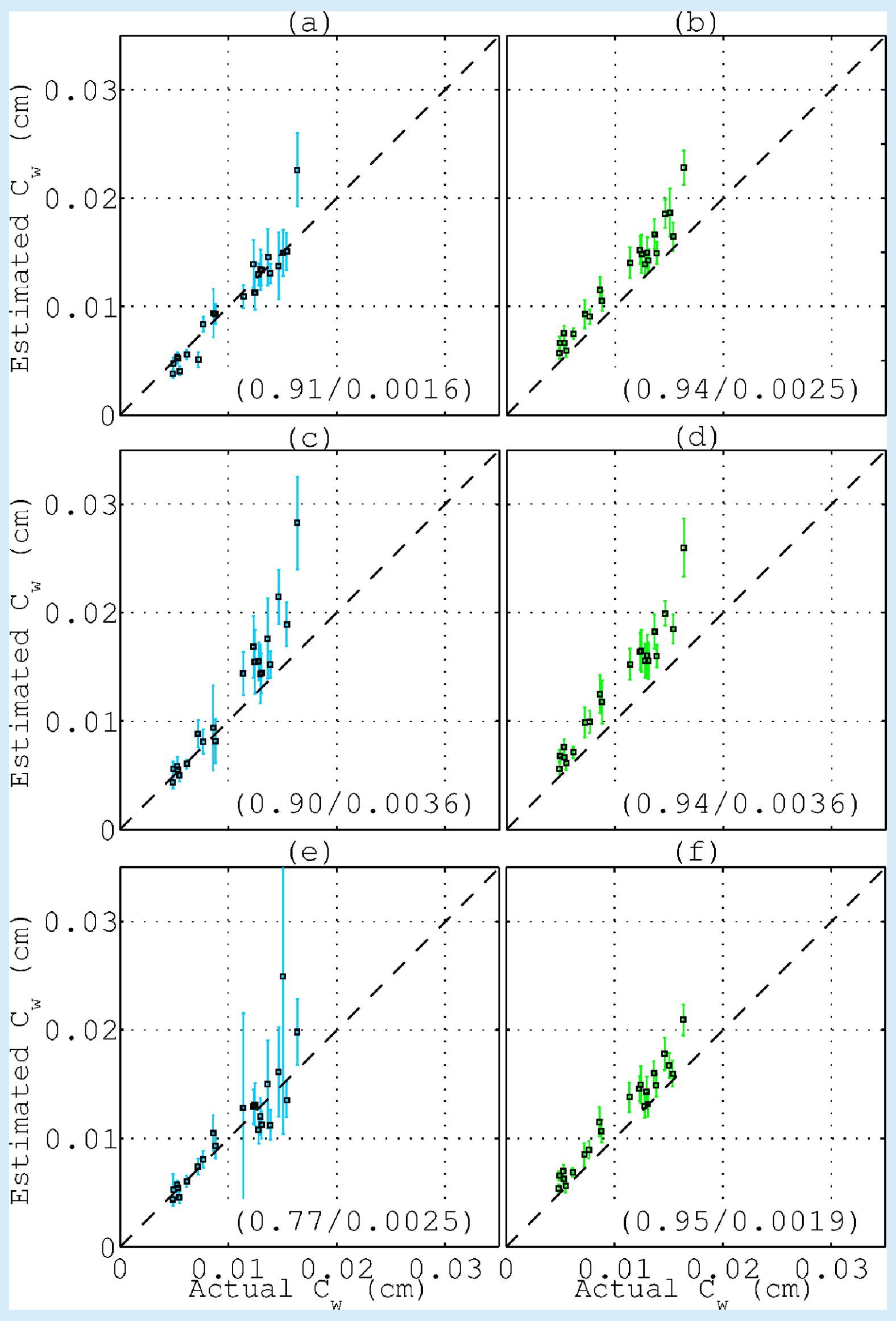


Figure: *C_w estimation results (mean +/- std) obtained with PROSPECT (blue) and PROCOSINE (green) with θ_i = 30˚(a-b), θ_i = 10˚(c-d) and θ_i = 50˚(e-f). R^2 and RMSE are given in parentheses.*

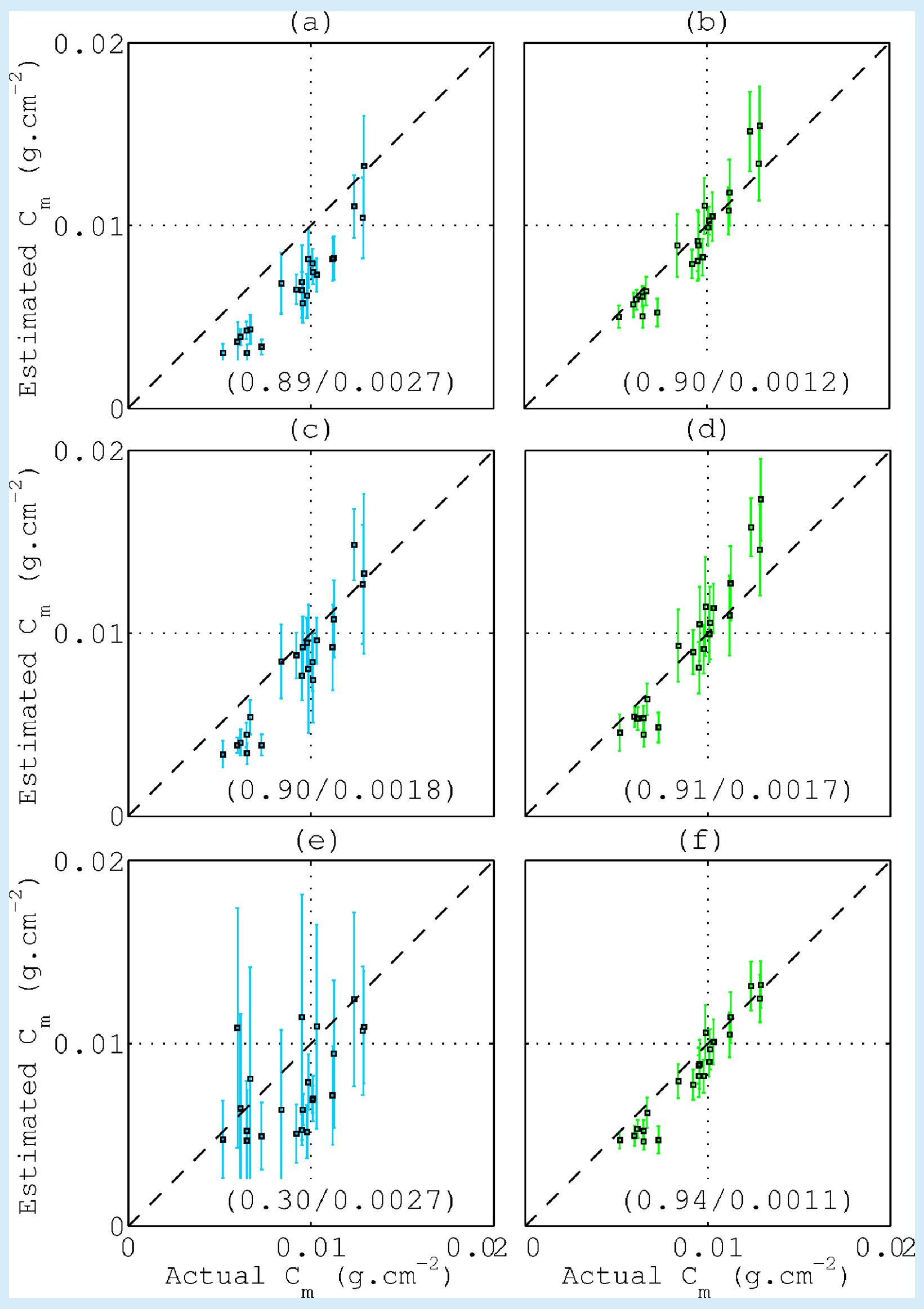


Figure: *C_m estimation results (mean +/- std) obtained with PROSPECT (blue) and PROCOSINE (green) with θ_i = 30˚(a-b), θ_i = 10˚(c-d) and θ_i = 50˚(e-f). R^2 and RMSE are given in parentheses.*

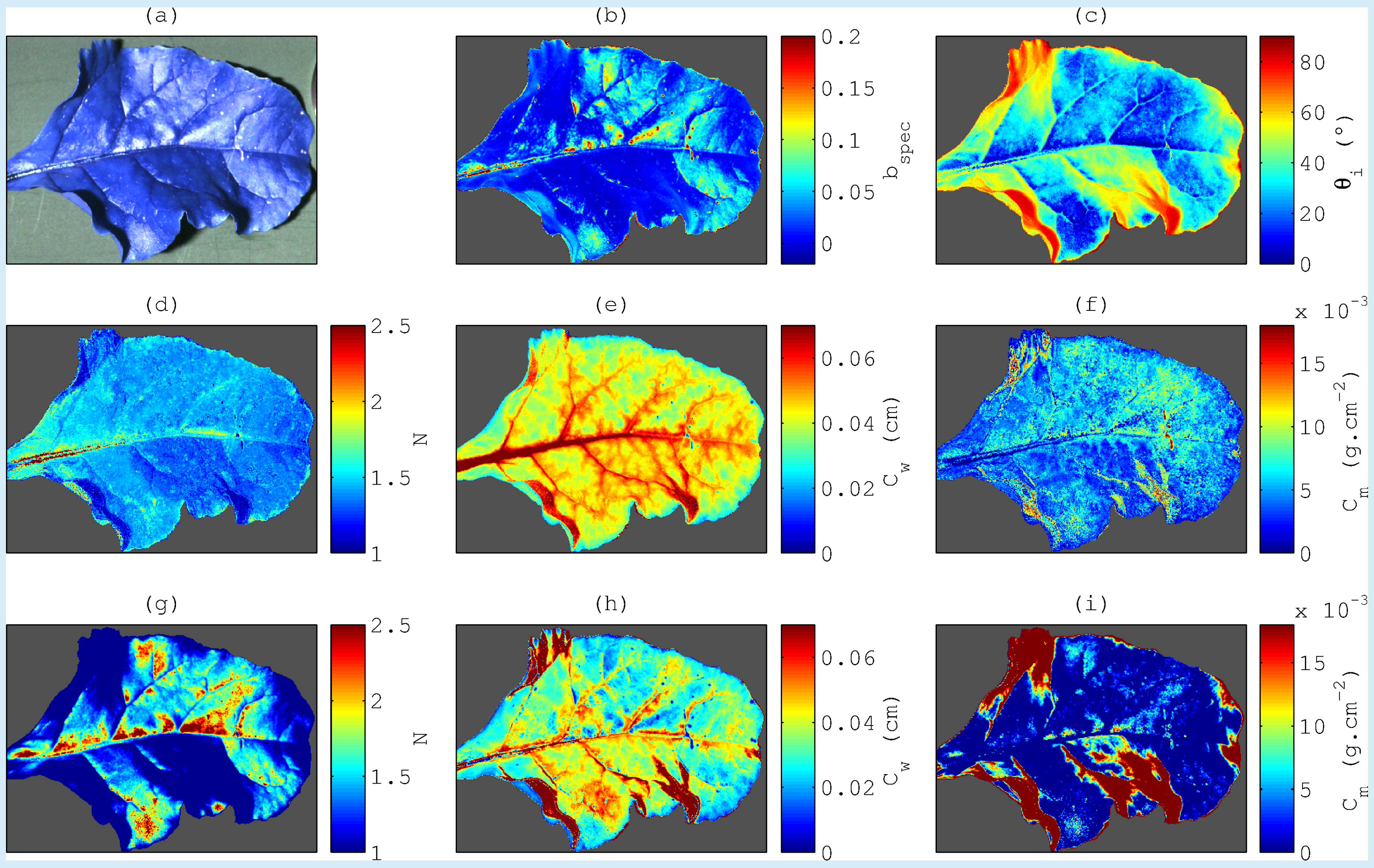
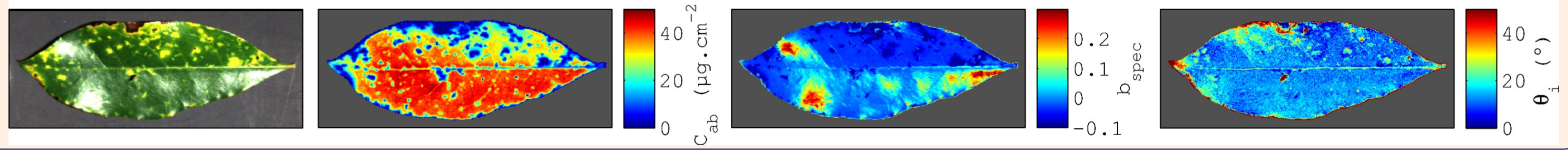


Figure: *Estimated maps obtained from an extra image using PROCOSINE (b-f) and PROSPECT (g-i). This sugar beet leaf is characterized by a high C_w value and a low C_m value (C_w = 0.036 cm, C_m = 0.004 g.cm^{-2}). (a) False color composite image (using bands 1458 nm, 2202 nm and 1662 nm), (b) b_{spec}, (c) θ_i, (d) N, (e) C_w, (f) C_m, (g) N, (e) C_w, and (f) C_m.*

Conclusions

- COSINE models specular reflection at the leaf surface and irregularities in leaf topography,
- The combined PROCOSINE model allows the submillimetric retrieval of leaf parameters,
- Also applicable to the VNIR range (400-1000 nm) for retrieving photosynthetic pigments (e.g., the chlorophyll content).



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