Photon recollision probability in forests - empirical evaluation and synergies with LiDAR

RAMI workshop, Varese, June 7th–9th 2023

Aarne Hovi, Daniel Schraik, Miina Rautiainen

Aalto University, Finland

This is a collaborative effort. Thank you!


Remote Sensing of Environment 293 (2023) 113610

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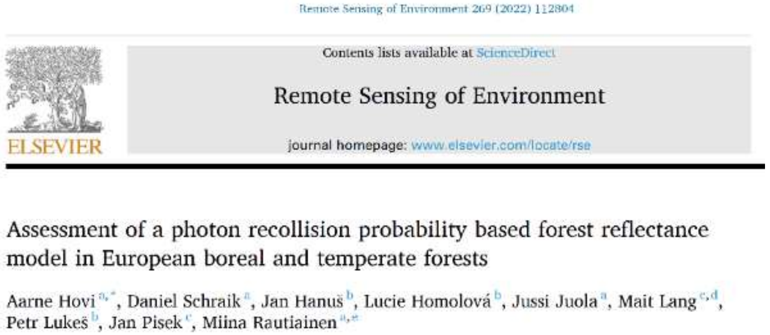
Synergistic use of multi- and hyperspectral remote sensing data and airborne LiDAR to retrieve forest floor reflectance

Aarne Hovi[a,*], Daniel Schraik[a], Nea Kuusinen[a], Tomáš Fabiánek[b], Jan Hanuš[b], Lucie Homolová[b], Jussi Juola[a], Petr Lukeš[b], Miina Rautiainen[a]


Remote Sensing of Environment 269 (2022) 112804

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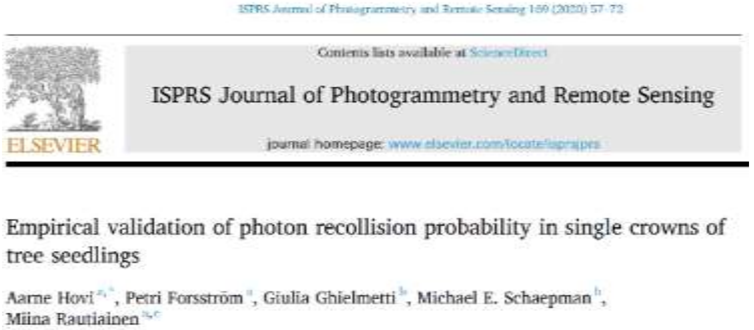
Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Assessment of a photon recollision probability based forest reflectance model in European boreal and temperate forests

Aarne Hovi[a,*], Daniel Schraik[a], Jan Hanuš[b], Lucie Homolová[b], Jussi Juola[a], Mait Lang[c,d], Petr Lukeš[b], Jan Pisek[c], Miina Rautiainen[a,e]


ISPRS Journal of Photogrammetry and Remote Sensing 169 (2020) 57–72

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ISPRS Journal of Photogrammetry and Remote Sensing

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Empirical validation of photon recollision probability in single crowns of tree seedlings

Aarne Hovi[a,*], Petri Forsström[a], Giulia Ghielmetti[b], Michael E. Schaepman[b], Miina Rautiainen[a,c]


Small geographical variability observed in Norway spruce needle spectra across Europe

Hovi A., Lukeš P., Homolová L., Juola J., Rautiainen M. (2022). Small geographical variability observed in Norway spruce needle spectra across Europe. Silva Fennica vol. 56 no. 2 article id 10683. 10 p. https://doi.org/10.14214/sf.10683


Evaluating the performance of a double integrating sphere in measurement of reflectance, transmittance, and albedo of coniferous needles

Hovi A., Mõttus M., Juola J., Manoocheri F., Ikonen E., Rautiainen M. (2020). Evaluating the performance of a double integrating sphere in measurement of reflectance, transmittance, and albedo of coniferous needles. Silva Fennica vol. 54 no. 2 article id 10270. 22 p. https://doi.org/10.14214/sf.10270


Remote Sensing of Environment 256 (2021) 112302

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Remote Sensing of Environment

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Multi-angular reflectance spectra of small single trees

Petri R. Forsström[a,*], Aarne Hovi[a], Giulia Ghielmetti[b], Michael E. Schaepman[b], Miina Rautiainen[a,c]

*

European Research Council

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Agricultural and Forest Meteorology 296 (2021) 108238

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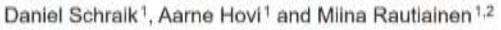
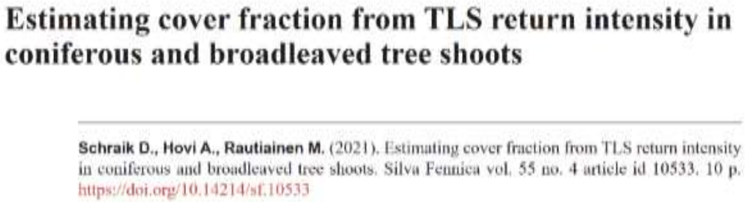
Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Crown level clumping in Norway spruce from terrestrial laser scanning measurements

Daniel Schraik[*,a], Aarne Hovi[a], Miina Rautiainen[a,b]


Daniel Schraik[1], Aarne Hovi[1] and Miina Rautiainen[1,2]


Estimating cover fraction from TLS return intensity in coniferous and broadleaved tree shoots

Schraik D., Hovi A., Rautiainen M. (2021). Estimating cover fraction from TLS return intensity in coniferous and broadleaved tree shoots. Silva Fennica vol. 55 no. 4 article id 10533. 10 p. https://doi.org/10.14214/sf.10533


RESEARCH ARTICLE

Ecology and Evolution

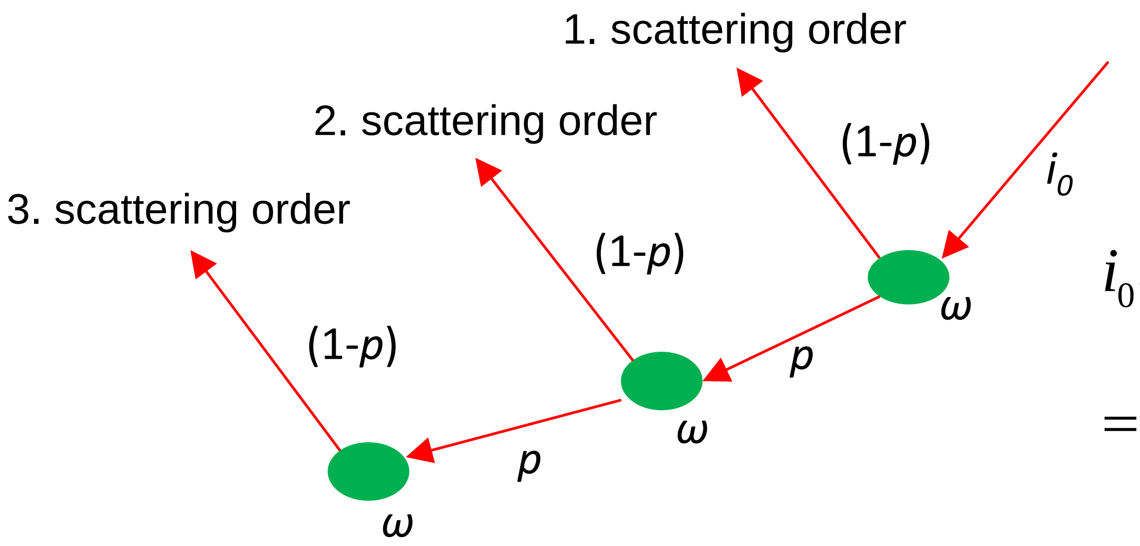
WILEY

A spectral analysis of stem bark for boreal and temperate tree species

Jussi Juola[1] | Aarne Hovi[1] | Miina Rautiainen[1,2]

Spectral invariants and photon recollision probability (*p*)

- Knyazikhin et al. (1998): vegetation canopy scattering can be modeled based on element spectra and spectrally invariant parameters
- Smolander and Stenberg (2005) **defined *p*** as "*(mean) probability by which a photon scattered from a leaf in the canopy will interact within the canopy again*"



$$i_0\omega_C = i_0\omega_L\left(1-p\right) + i_0\omega_L p\omega_L\left(1-p\right) + \ldots$$

$$= i_0\,\frac{\omega_L\left(1-p\right)}{1-p\omega_L}$$

- *p* is related to canopy gap fractions (or interception) and leaf (plant) area index

  → direct link between vegetation structure and scattering properties

$$p = 1 - \frac{i_D}{\mathrm{LAI}}$$

Knyazikhin et al. 1998. J. Geophys. Res. Atmos. 103 (D24): 32257–32275, Smolander and Stenberg 2005. Rem. Sens. Environ. 94: 355–363

Spectral invariants and *p*

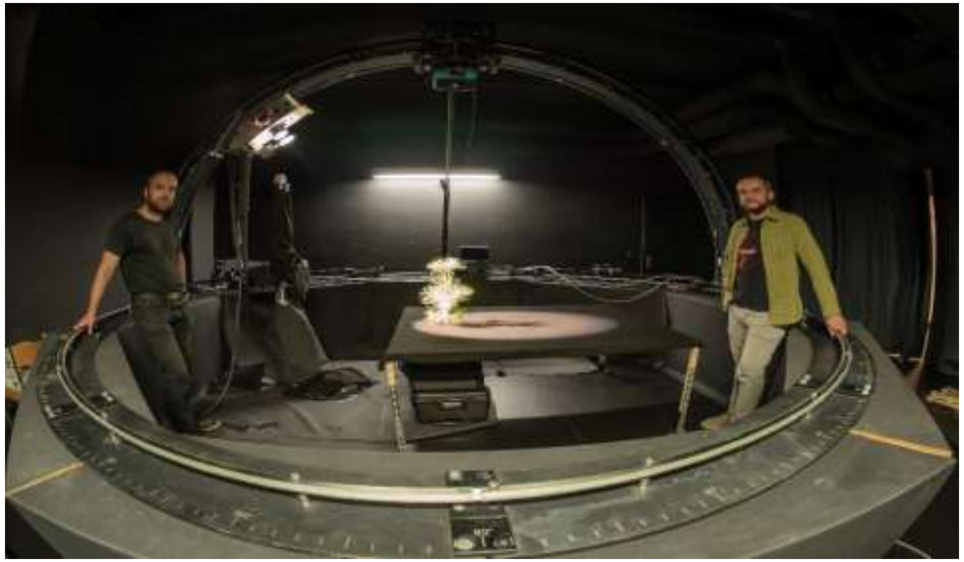
- Example applications:
  - modeling reflectance/albedo (Stenberg et al. 2013, Hadi et al. 2017, Hovi et al. 2017, Hadi and Rautiainen 2018, Manninen et al. 2021)
  - modeling sun-induced fluorescence (Zeng et al. 2020)
  - retrieval of vegetation biophysical parameters (Myneni et al. 2002, Ganguly et al. 2012, Varvia et al. 2018, Schraik et al. 2019)
  - explaining links between biophysical parameters and reflectance (Knyazikhin et al. 2013, Zeng et al. 2022)

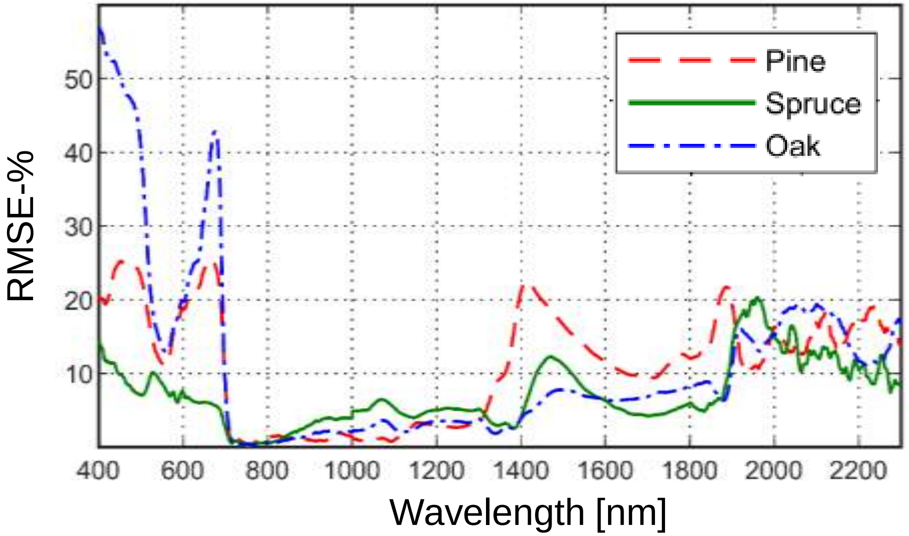
- Gaps in knowledge:
  - **Empirical evaluations** of the theories **limited**
    - often **small geographical coverage**
    - **uncertain** due to limited measurements
  - **Synergies with LiDAR** not explored

Ganguly et al. 2012. Remote Sens. Environ. 122: 185–202
Hadi et al. 2017. Remote Sens. Environ. 201: 314–330
Hadi and Rautiainen 2018. Remote Sens. Lett. 9: 666–675
Hovi et al. 2017. Agric. For. Meteorol. 247: 331–342
Knyazikhin et al. 2013. PNAS 10 (3): E185–E192
Manninen et al. 2021. J. Geophys. Res. Atmos. 127: e2021JD035376
Myneni et al. 2002. Remote Sens. Environ. 83: 214–231
Schraik et al. 2019. J. Quant. Spectrosc. Radiat. Transf. 233: 1–12
Stenberg et al. 2013. Remote Sens. Environ. 137, 12–16
Varvia et al. 2018. J. Quant. Spectrosc. Radiat. Transf. 208: 19–28
Zeng et al. 2020. Remote Sens. Environ. 240: 111678
Zeng et al. 2022. Nat. Rev. Earth Environ. 2022

Test with single trees (in collaboration with Uni. Zurich)

Hovi et al. 2020. ISPRS J. Photogramm. 169: 57–72 *





- Multiangular measurements of small trees were simulated with a *p*-based model
- Some differences due to directional scattering properties of the trees and the foliage orientation

→ Mainly successful and motivated to continue with field experiments

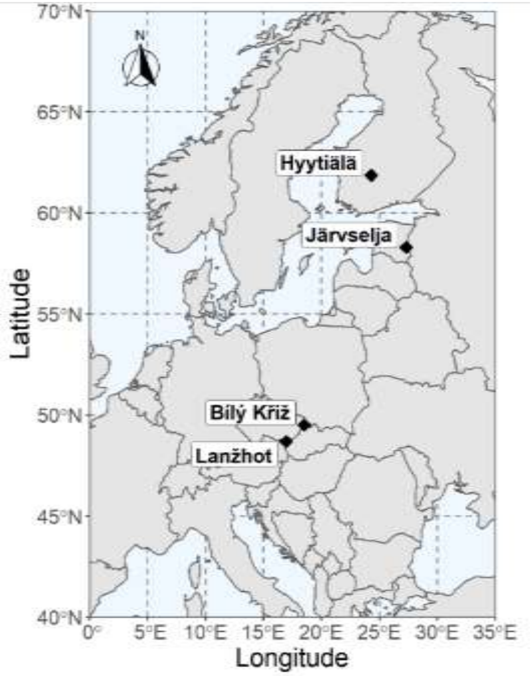
* For description of the measurements, see also:

Forsström et al. 2021. Remote Sens. Environ. 255: 112302.

Hovi et al. 2021. Data in Brief 35: 106820.

Field campaigns

- Data from **50 (66) forest plots** in boreal, hemiboreal, and temperate forests



Model validation

Airborne hyperspectral

Canopy spectral transmittance

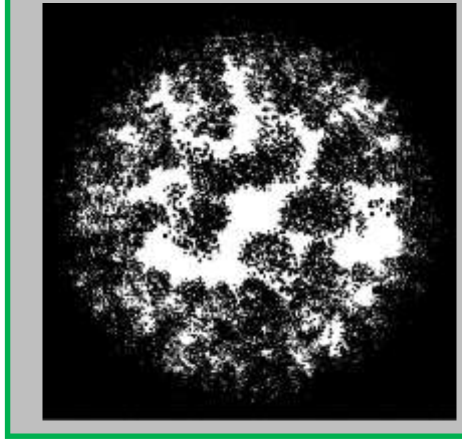
Structural parameters

Hemispherical photos

Forest inventory (tree species)

Structural parameters (new data sources)

Airborne LiDAR



Terrestrial LiDAR

Specral parameters

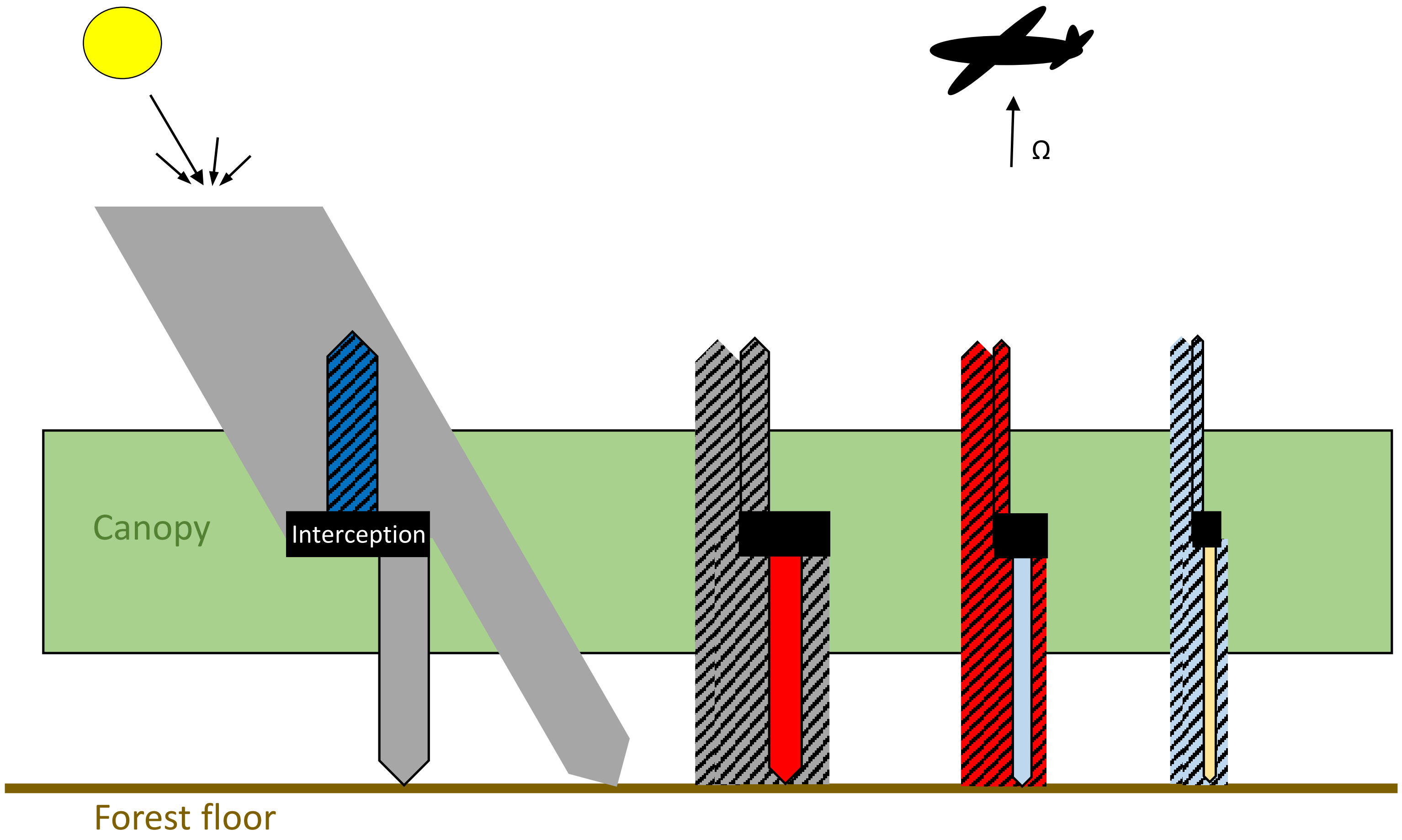
Foliage spectra

Bark spectra

Forest floor spectra

Test in forest canopies (in collaboration with Tartu Observatory and CzechGlobe)

- PARAS forest reflectance model (Rautiainen and Stenberg 2005)
- Modified to account for
  - multiple scattering between canopy and understory
  - directional scattering properties of the canopy
  - contribution of woody elements
- **Model evaluation against airborne hyperspectral data**
- **Canopy structure parameterization with traditional sources (hemisph. photos, forest inventory)**



$$R = i_0 Q\omega_C + (1-i_0) R_G (1-i_\Omega)$$

$$R = i_0 Q_\Omega Q\omega_C + \left[(1-i_0)+i_0(1-Q)\omega_C\right] R_G \left[(1-i_\Omega)+i_D(1-Q)\omega_C\right]\frac{1}{1-R_G i_D Q\omega_C}$$

Rautiainen and Stenberg 2005. Remote Sens. Environ. 96: 98–107.
Hovi et al. 2022. Remote Sens. Environ. 269: 112604

Test in forest canopies (in collaboration with Tartu Observatory and CzechGlobe)

Hovi et al. 2022. Remote Sens. Environ. 269: 112604

$$R = i_0 Q_\Omega Q \omega_C + \left[(1-i_0) + i_0(1-Q)\omega_C\right] R_G \left[(1-i_\Omega) + i_D(1-Q)\omega_C\right] \frac{1}{1-R_G i_D Q \omega_C}$$

$$Q_\Omega = 0.71 \frac{i_\Omega}{i_D}$$

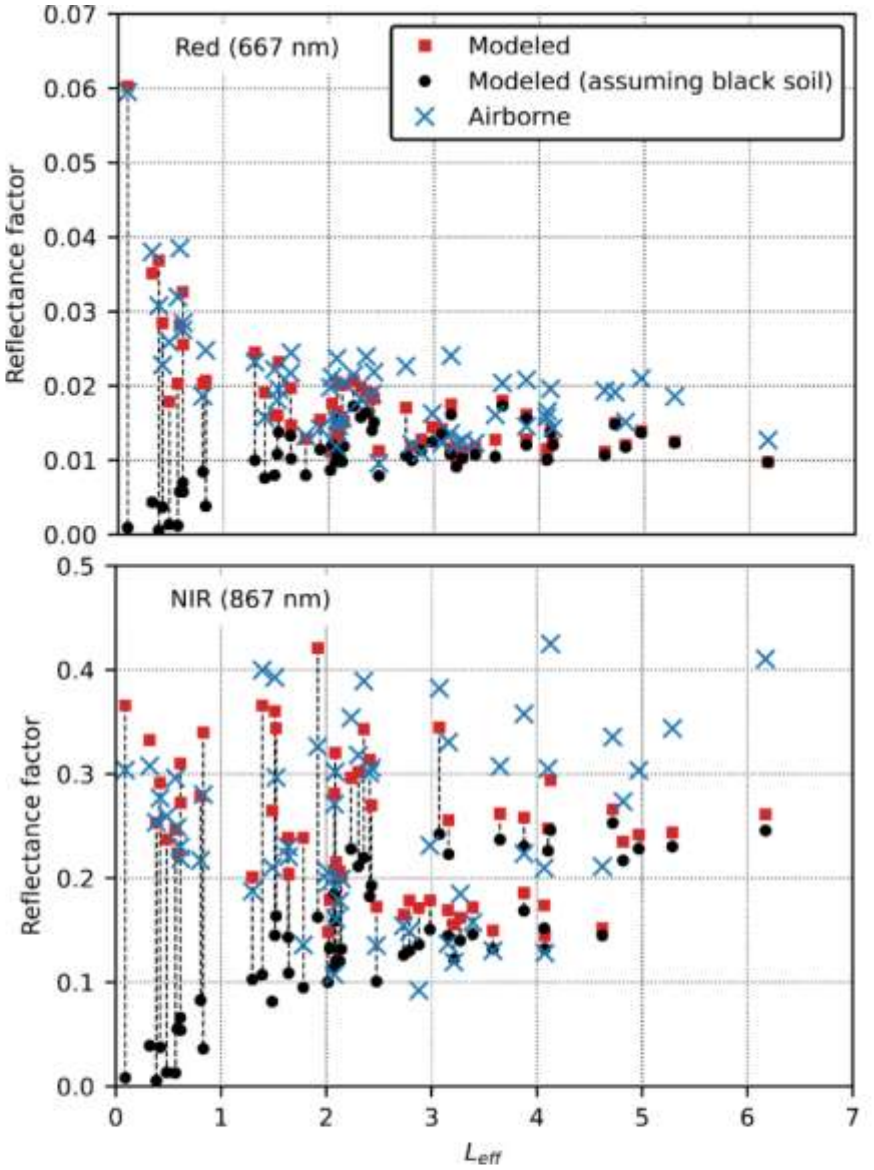
Directional scattering properties

$$\omega_C = \frac{(1-p)\omega_E}{1-p\omega_E}$$

$$\omega_E = \sum_{sp} \left\{ f_{sp} \left[f_{W,sp}\omega_{W,sp} + (1-f_{W,sp})\omega_{S,sp} \right] \right\}$$

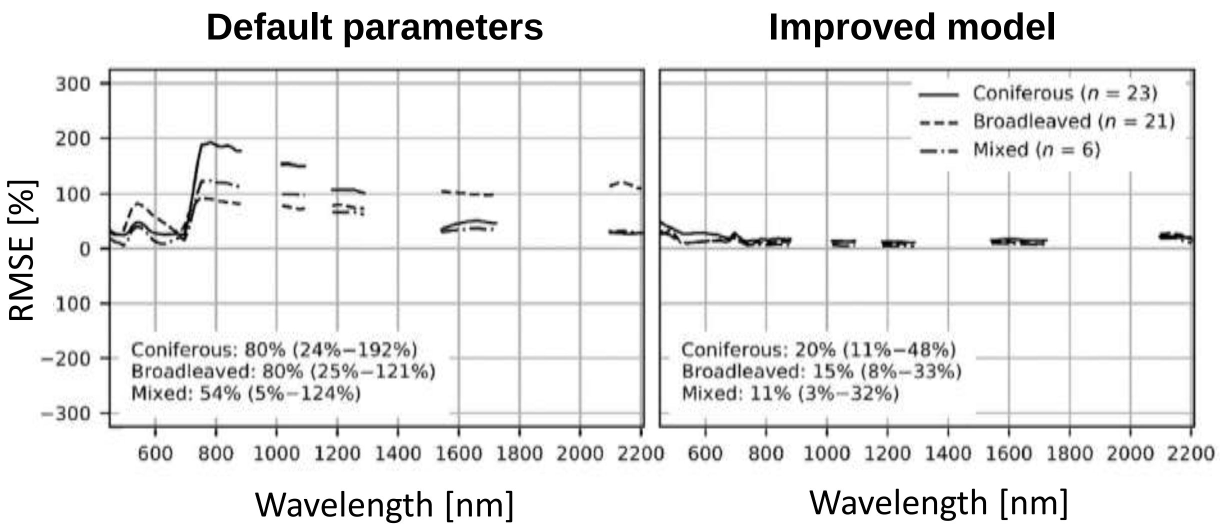
Woody elements

- ➢ The improved model predicts dependence of forest reflectance factors on plant area index and tree species correctly
- ➢ (Random) errors for individual forest stands can be large

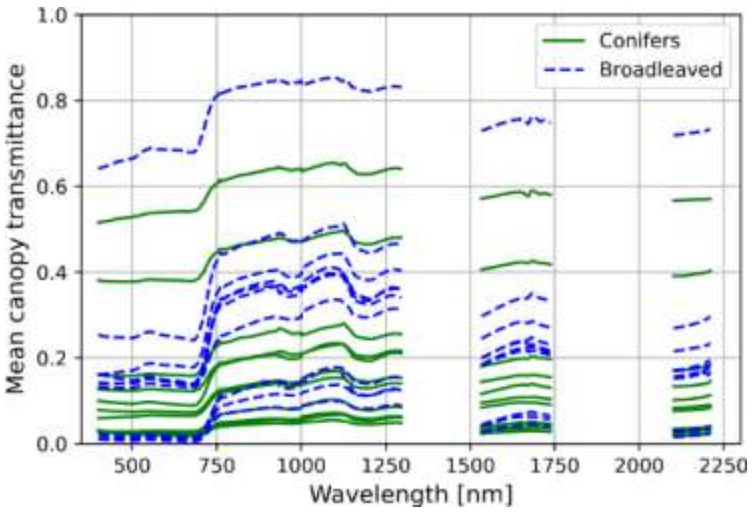


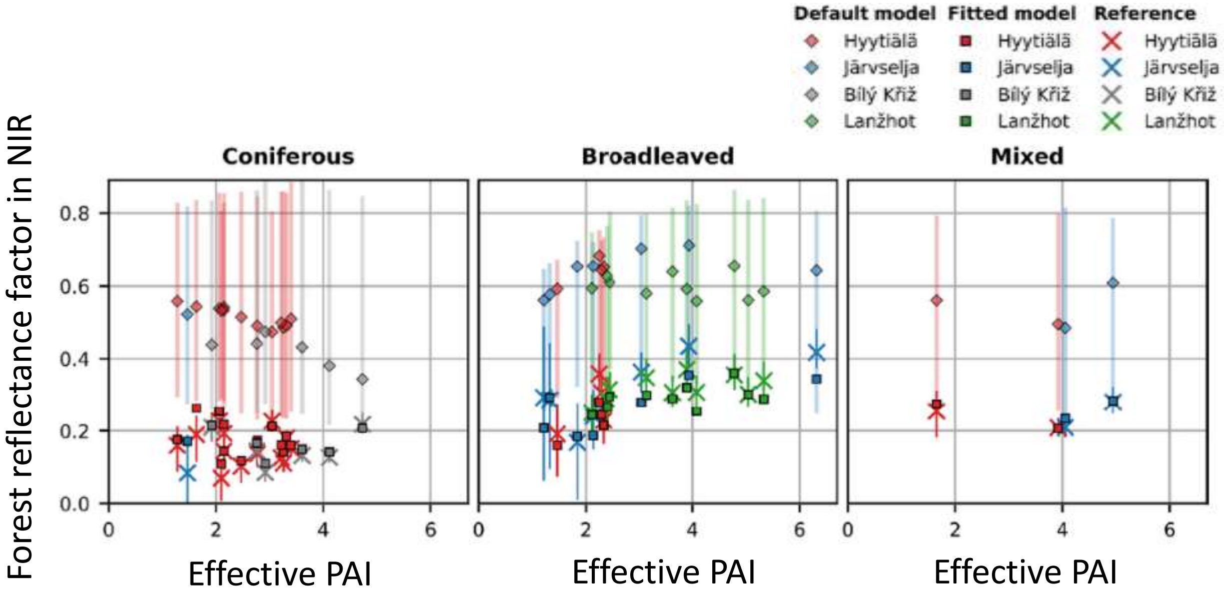
Test in forest canopies (in collaboration with Tartu Observatory and CzechGlobe)

Hovi et al. 2022. Remote Sens. Environ. 269: 112604



- ➢ New parameters were estimated by fitting them to the data (model inversion)
- ➢ The inverted parameter values (woody element fraction, nadir to hemispherical reflectance ratio) were physically meaningful
- ➢ Canopy **spectral transmittance measurements** helped to constrain the inversion



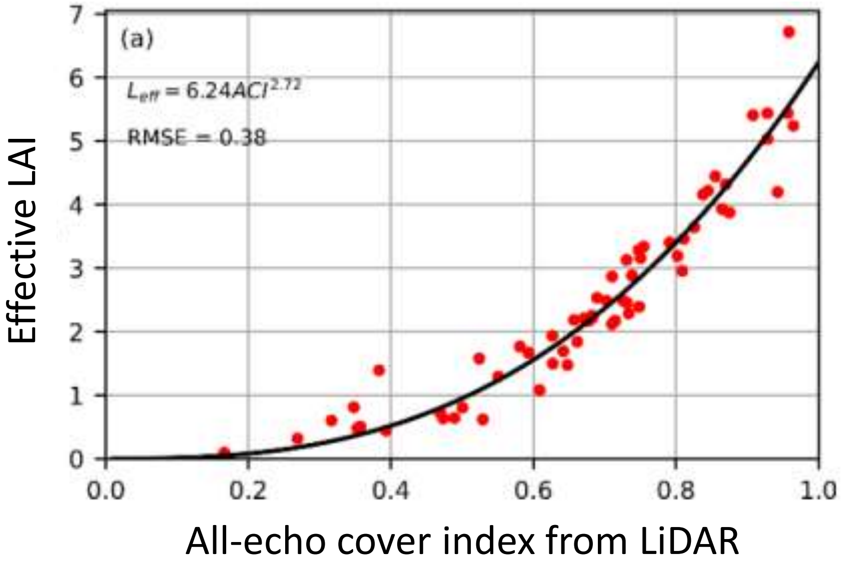


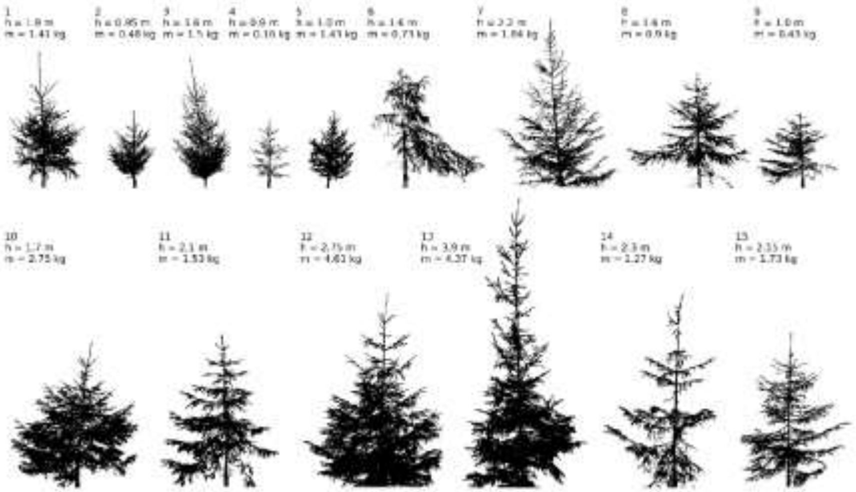
Synergies with lidar data

- Lidar as data source for model input parameters
  - Canopy gap fractions (interception)
  - Leaf (plant) area index
  - Photon recollision probability

$$p = 1 - \frac{i_D}{\mathrm{LAI}}$$

- Airborne and terrestrial lidar are becoming the most accurate measurement methods for canopy structure, also for RT modeling
- Airborne lidar is widely available from many countries
- Terrestrial lidar provides extremely fine details of canopy structure

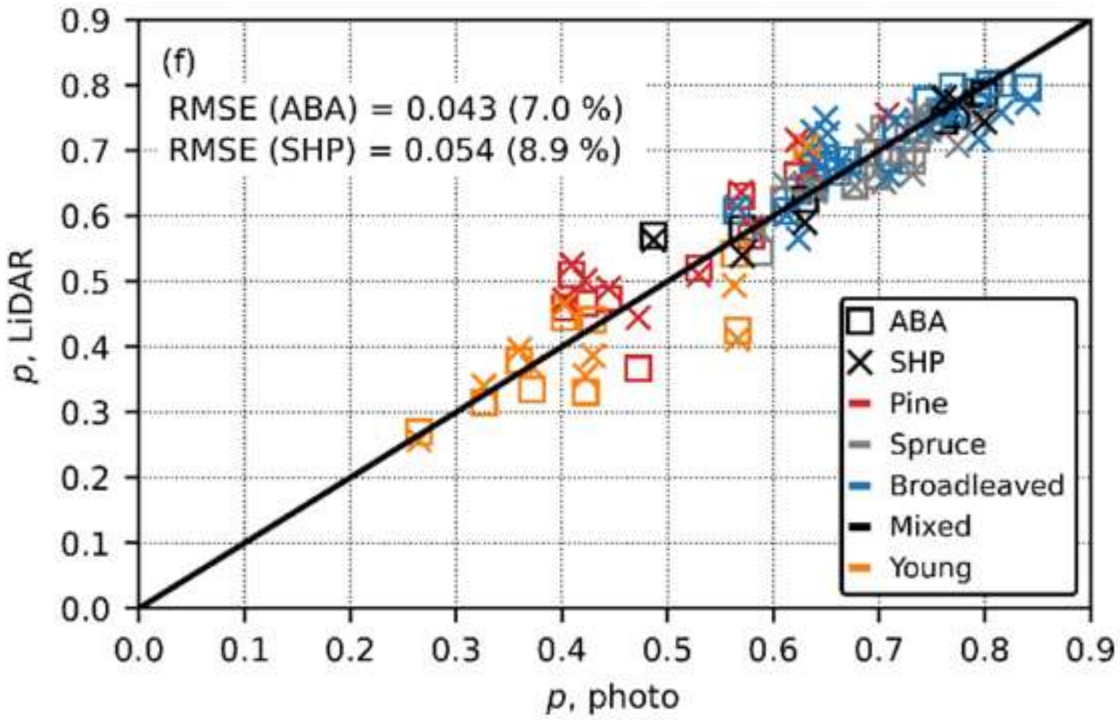


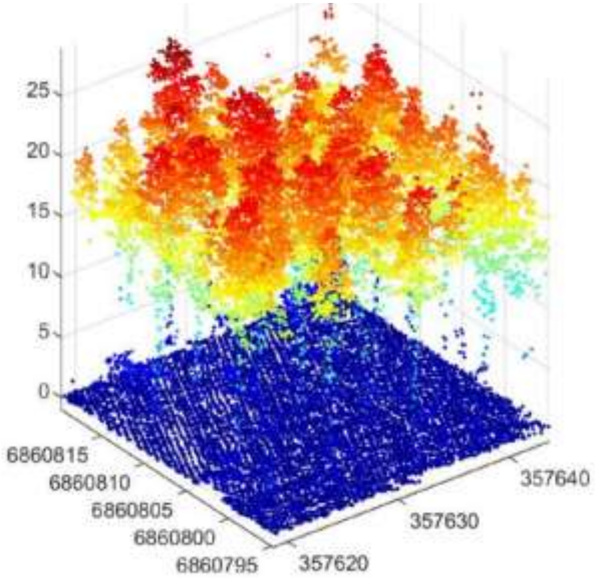


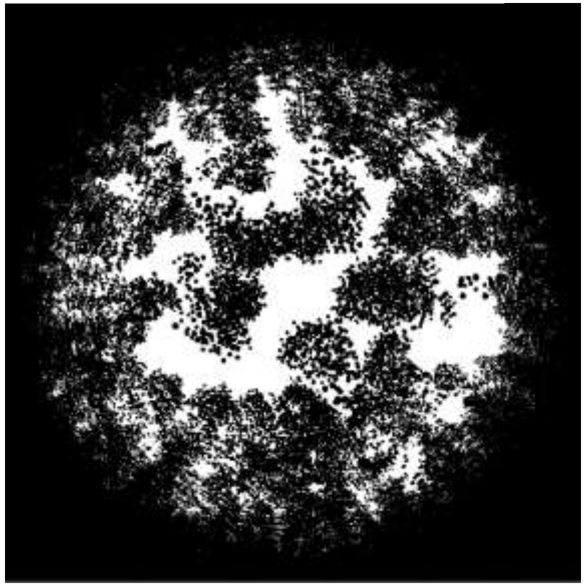
Schraik et al. 2021. Agric. For. Meteor. 296: 108238

Airborne lidar

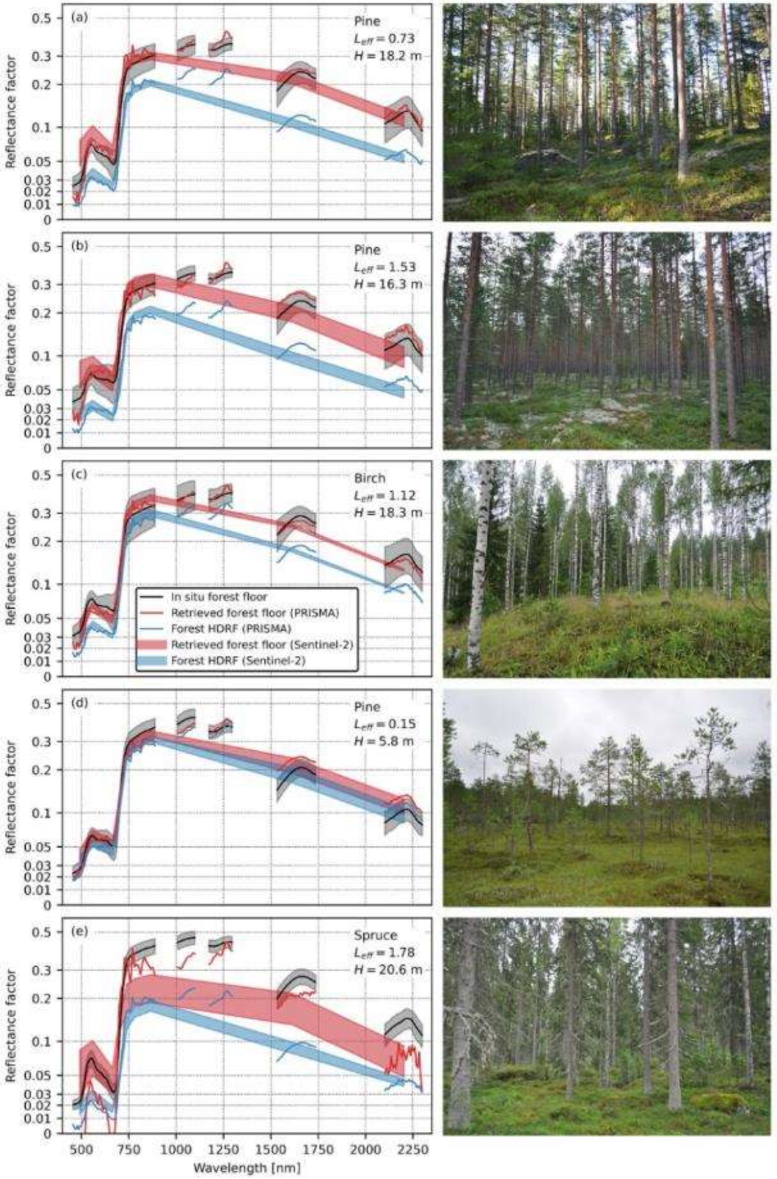
- ➢ Area-based approach (ABA)
  - ➢ All-echo cover index
  - ➢ Ratio of number of canopy to total echoes
  - ➢ Logistic regression of angular interceptance
- ➢ Synthetic hemispheric photographs (SHPs)
  - ➢ Ray tracing
  - ➢ Point cloud as spheres with size inverse proportional to point density
- ➢ Good correspondence to *in situ* HPs of both approaches
- ➢ ALS input for PARAS model was equally good as *in situ* HP measurements



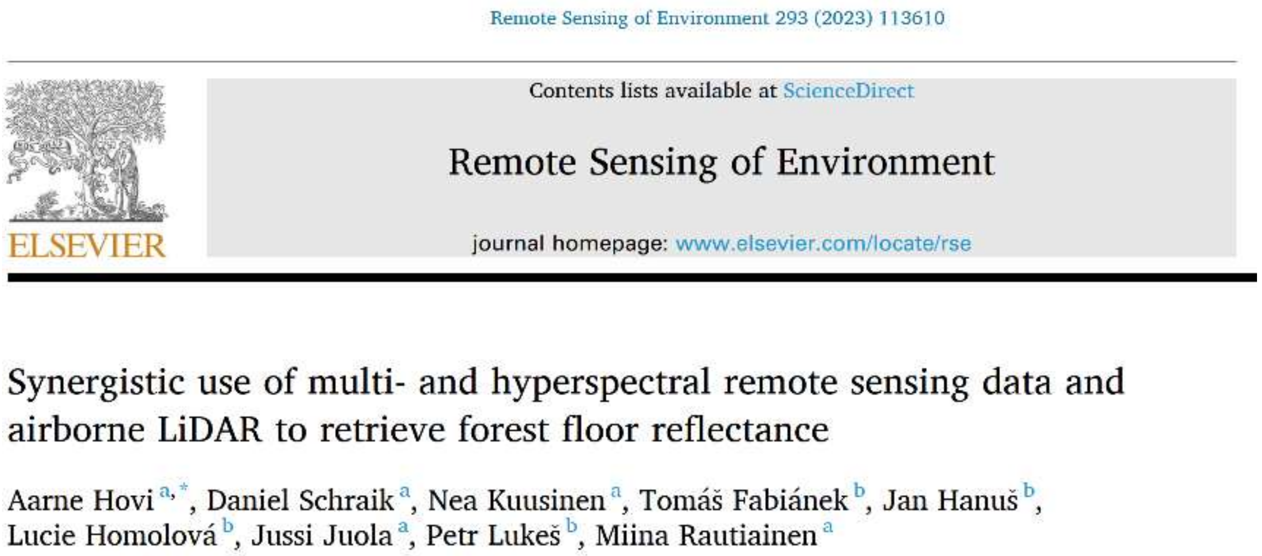




Application in estimating forest floor spectra



- ➢Mapping forest floor reflectance with ALS-derived input
- ➢Sentinel-2 and PRISMA images



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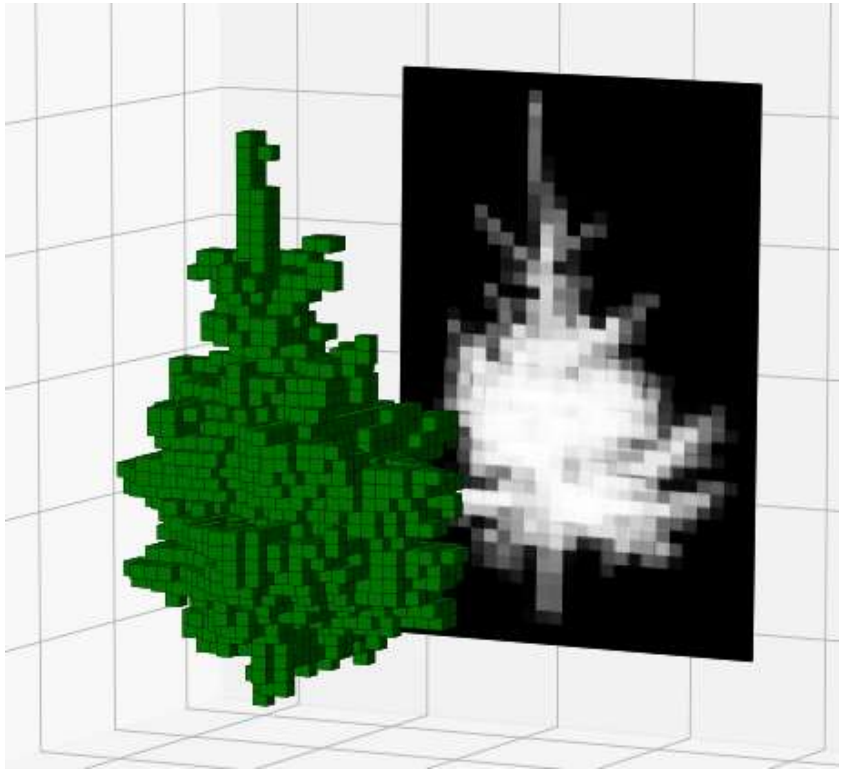
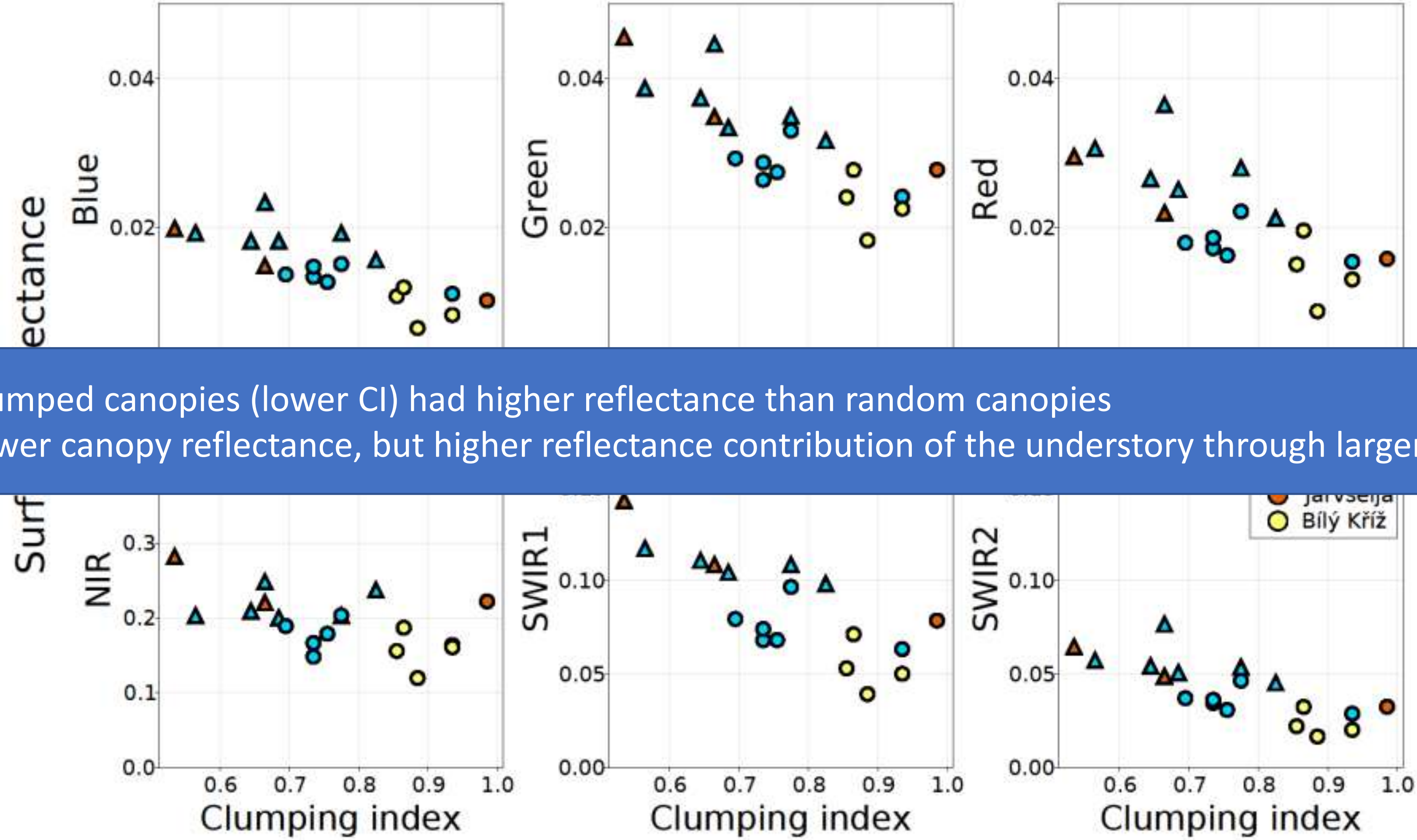
Terrestrial lidar

- Three-dimensional quantification of canopy leaf area density
- Ray tracing beams' path length through a voxel volume
- Parametrization of a Poisson canopy from this data requires **compactification**
- Photon recollision probability $p = 1 - \frac{i_D}{\mathrm{LAI}}$
- LAI or total leaf area – summation
- Diffuse interceptance i_D
    - Ray tracing
    - Spherical averaging
- Provides canopy clumping index at scales above voxel size



Schraik et al. 2021. Agric. For. Meteor. 296: 108238

TLS canopy clumping and bottom-of-atmosphere reflectance



- ➢Clumped canopies (lower CI) had higher reflectance than random canopies
- ➢Lower canopy reflectance, but higher reflectance contribution of the understory through larger gaps

Conclusions

Thank you!

- *p*-based model is computationally efficient and easy to parameterize based on leaf (plant) area index, canopy gap fractions, and forest floor and canopy element spectra
- Improvements to PARAS model increased performance
  - Multiple scattering
  - Woody elements
  - Non-Lambertian canopy scattering
- Lidar provides useful synergies both in large area applications (ALS) and in quantifying canopy structure in high detail (TLS)
- Extensive empirical validation helped assess model performance in different forests in Europe (Finland, Estonia, Czechia)
  - Dataset to be published soon
- Further improvements are coming, stay tuned!

Aalto-yliopisto

European Research Council
Established by the European Commission

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