<u>Response to</u>: Townsend et al., "Disentangling the contribution of biological and physical properties of leaves and canopies in imaging spectroscopy data"

DECOUPLING CONTRIBUTIONS FROM CANOPY STRUCTURE AND LEAF OPTICS IS CRITICAL FOR REMOTE SENSING LEAF BIOCHEMISTRY

Yuri Knyazikhin[1], Philip Lewis[2], Mathias I. Disney[2], Pauline Stenberg[3], Matti Mõttus[4], Miina Rautiainen[3], Robert K. Kaufmann[1], Alexander Marshak[5], Mitchel A. Schull[6], Pedro Latorre Carmona[7], Vern Vanderbilt[8], Anthony B. Davis[9], Frédéric Baret[10], Stéphane Jacquemoud[11], Alexei Lyapustin[12], Yan Yang[1] and Ranga B. Myneni[1]

[1]Department of Earth and Environment, Boston University, Boston, MA 02215; [2]Department of Geography and National Centre for Earth Observation, University College London, London WC1E 6BT, United Kingdom; Departments of [3]Forest Sciences and [4]Geosciences and Geography, University of Helsinki, FI-00014, Helsinki, Finland; [5]Climate and Radiation Laboratory, Code 613, National Aeronautics and Space Administration Goddard Space Flight Center, Greenbelt, MD 20771; [6]Hydrology and Remote Sensing Laboratory, US Department of Agriculture– Agricultural Research Service, Beltsville, MD 20705; [7]Departamento de Lenguajes y Sistemas Informáticos, Universidad Jaume I, 12071 Castellón, Spain; [8]Biospheric Science Branch, Earth Science Division, National Aeronautics and Space Administration–Ames Research Center, Moffet Field, CA 94035; [9]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109; [10]Unité Mixte de Recherche 1114 Environnement Méditerranéen et Modélisation des Agro-Hydrosystèmes, Institut National de la Recherche Agronomique Site Agroparc, 84914 Avignon, France; and [12]Institut de Physique du Globe de Paris–Sorbonne Paris Cité, Université Paris Diderot, Unité Mixte de Recherche Centre National de la Recherche Scientifique 7154, 75013 Paris, France

Townsend et al. (1) agree that we explain the observed relationship (2) between foliar nitrogen (%N) and near-infrared (NIR) canopy reflectance is largely due to structure - i.e., structural variation due to fraction of broadleaf canopy. Our conclusion that the observed correlation with %N is spurious (i.e., lacking a causal basis) is thus clearly justified: we demonstrate that structure explains the great majority of observed correlation, where the structural influence is derived precisely via reconciling the observed correlation with radiative transfer theory. What this also suggests is that such correlations, although observed, do not uniquely provide information on canopy biochemical constituents. We therefore disagree with assertion in ref. (1) that we "*do not provide adequate rationale for the inference that %N and other leaf properties cannot be characterized from imaging spectroscopy*" - our analysis shows precisely that. Our analysis also leads to the conclusion that "*NIR and/or SW broadband satellite data cannot be directly linked to leaf-level processes*" and any such link must be indirect and will be a function of structure. This is true *for all wavelengths* in the interval 423-850nm (Figs. 7b and S2 in ref. (3)), not primarily for the 800-850 nm spectral band as misstated in ref. (1). None of the leaf biochemical constituents can be accurately estimated without removal of canopy structural effects.

We identified a new structural variable, the Directional Area Scattering Factor (DASF), which is determined entirely by canopy geometrical properties such as shape and size of the tree crowns, spatial distribution of trees on the ground, within-crown foliage arrangement and properties of the leaf surfaces. In dense vegetation, this parameter can be directly retrieved from the reflectance spectrum *without the use of canopy reflectance models*, *prior knowledge, or ancillary information regarding leaf optical properties* (3). Equations [S4.1] – [S5.3] in ref. (3) explain the background physics, but Townsend et al. (1) nonetheless misinterpret this as "*the authors utilized a single leaf spectrum derived from one PROSPECT simulation*." We clearly demonstrated that DASF provides information critical to accounting for structural contributions to measurements of leaf biochemistry from space.

Lastly, we do not claim that "*links between leaf biochemistry (e.g., %N) and hyperspectral reflectance data are obscured by variation in leaf surface albedo*" as overstated in ref. (1). We emphasized that some radiation is scattered at the surface of leaves and therefore contains no information on leaf biochemistry; this presents an additional confounding factor, unless it can be accounted for.

Statistical relationships between leaf biochemistry and canopy reflectance spectra have indeed been repeatedly demonstrated. However, analyses of underlying physical mechanisms that generate the remotely measured signal, which are required to distinguish causality from correlation (4), *such as ours*, have been lacking thus far. This is absolutely necessary to obtain accurate information on leaf biochemistry from space (5). We agree that analyses including both biologically and physically-based approaches will help reveal the subtleties of the empirical relationships.

REFERENCES

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