An Investigation on Sieve and Detour Effects Affecting the Interaction of Collimated and Diffuse Infrared Radiation (750 to 2500 nm) With Plant Leaves

Gladimir V. G. Baranoski, *Member, IEEE*, and Denise Eng

***Abstract*—The retrieval of plant biophysical and biochemical properties from high spectral resolution data represents an active area of research within the remote sensing field. Scientific studies in this area are usually supported by computational simulations of light attenuation processes within foliar tissues. In heterogeneous organic materials, like plant leaves, sieve and detour effects can affect these processes and ultimately change the light gradients within these tissues and their spectral signatures. Although these effects have been extensively examined for applications involving the interactions of visible radiation with plant leaves, little is known about their role in the infrared domain. In this paper, we describe the procedural basis for their incorporation in the modeling of infrared-radiation transport (in the range of 750–2500 nm) within plant leaves. We also assess their impact on the predictability of simulation solutions relating the directionality of the incident radiation and the internal arrangement of the tissues to changes on foliar spectral signatures in this domain. Our investigation is grounded by the observations involving the modeled results and quantitative and qualitative data reported in the literature.**

***Index Terms*—Absorption, detour effect, leaves, scattering, sieve effect.**

I. INTRODUCTION

THE MEASUREMENT and modeling of foliar optical properties are the objects of extensive research in remote sensing and related fields. As a result, a substantial number of models have been developed to simulate light interactions with plant leaves [1], with potential target applications ranging from the estimation of foliar biophysical parameters through inversion procedures [2] to the analysis of plant responses to environmental changes [3]. The key task performed by these models involves the simulation of light attenuation within the foliar tissues, which causes a reduction in the internal photon fluence rate. This reduction, which is known as light gradient [4], is associated with variations in the penetration depth [5] and trapping of the incident light [6]. Accordingly, its study and modeling can provide valuable tools for the analysis of changes in the spectral signature of plants due to nutrient and water stress [7] and enhance the current understanding of photobiological phenomena such as photosynthesis, phototropism, and photomorphogenesis [8], [9].

The foliar light gradient is affected by both the directional quality of the incident light [9]–[11], which enters the leaf either through collimated radiation (e.g., direct sunlight [12]) or diffuse radiation (e.g., skylight [12]), and the foliar structural and biophysical characteristics, which determine the degree of attenuation of light being propagated within the leaf. Although it is possible to estimate the probability of a photon being attenuated within a foliar tissue either due to scattering or absorption, it is important to note that these two processes are intertwined [13]. Hence, for modeling purposes, the computation of the absorption probability needs to account for structural factors affecting the propagation of light under *in vivo* conditions. Due to the nonhomogeneous distribution of absorbers within the foliar tissues, light can be propagated without encountering these foliar constituents, which is a phenomenon known as sieve effect [4], [14]–[16]. Alternatively, when the propagated light encounters an absorber, its direction of propagation can be changed, which is a phenomenon known as detour effect [4], [14], [15], [17]. These phenomena have opposite influences on the absorption of light within the foliar tissues: The sieve effect reduces the probability of light absorption within these tissues, while the detour effect enhances it [13], [14], [18].

Detour and sieve effects have been extensively studied and measured with respect to the propagation of visible light in foliar tissues and its interaction with photosynthetic pigments [15]–[17], [19], [20]. However, to the best of our knowledge, quantitative data regarding the role of these effects in interactions of infrared radiation with these tissues are not readily available in the scientific literature. We remark that investigations involving foliar light regime in the near (700–1300 nm) and middle (1300–2500 nm) infrared regions [21] are central to the characterization of leaf constituents of high value from an industrial and agricultural standpoint, such as cellulose, starch, lignin, and protein [7], [21], and to the assessment of water stress in regions of vegetation [22], [23]. In this paper, we examine the algorithmic simulation of these effects in the infrared domain from 750 to 2500 nm, henceforth referred to as the investigated spectral domain. More specifically, we target

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modeling efforts relating the directionality of incident infrared radiation in this domain to variations of foliar photon transport patterns. We also address aspects affecting the quantitative accuracy of such simulations and discuss future prospects in this area.

II. PROCEDURAL SIMULATION OF SIEVE AND DETOUR EFFECTS

Recently, Baranoski [24] proposed two models, which are the algorithmic BDF (bidirectional scattering distribution function) model for bifacial leaves (ABM-B) and the algorithmic BDF model for unifacial leaves (ABM-U), to algorithmically simulate the interaction of infrared radiation (in the range of 750–2500 nm) with bifacial and unifacial plant leaves, respectively. Bifacial leaves are characterized by a differentiated mesophyll tissue. In these leaves, this tissue is usually composed of one or more layers of palisade cells and a loosely packed layer of spongy cells [25]. Unifacial leaves, on the other hand, are characterized by an undifferentiated mesophyll tissue. In monocotyledon species with unifacial leaves, this tissue visually resembles the spongy layer of bifacial leaves but with a smaller portion of its volume occupied by air [26], [27].

In this section, for the sake of completeness, we describe how sieve and detour effects were incorporated in the absorption testing performed by the ABM-B and ABM-U. The emphasis is on the unpublished issues related to the procedural simulation of these effects. For general information about these models, the reader is referred to the publication of Baranoski [24].

The infrared absorption testing performed by the ABM-B and ABM-U is based on a modified Beer–Lambert law which geometrically accounts for changes in the optical-path length due to sieve and detour effects. These changes are often quantified in terms of a factor of intensification [19] or apparent scattering path length [16] in remote-sensing-related applications and differential path length factor in biomedical applications [28]. As mentioned earlier, although these changes on the optical path have been investigated with respect to the presence of photosynthetic pigments, such as chlorophyll and carotenoids, which are relevant in the visible domain, to the best of our knowledge, neither its quantification with respect to the foliar absorbers acting in the investigated spectral domain nor a unified theory of sieve and detour effects is currently available in the literature. For this reason, the sieve and detour effects were incorporated in the ABM-B and ABM-U using a nondeterministic approach based on qualitative information inferred from the available data.

In the ABM-B and ABM-U, light transport is simulated as a random-walk process whose states correspond to the main tissue interfaces found in bifacial and unifacial leaves, respectively. The transition probabilities of this random walk are associated with the Fresnel coefficients computed at each interface, and the termination probabilities are associated with the free path length of the ray (photon) traveling in the mesophyll tissue. Once a ray at a certain wavelength λ enters the mesophyll tissue, it may be propagated or absorbed. The absorption probability is given by

$$\mathcal{P}(\lambda) = 1 - \epsilon^{-\mu_{\mathrm{a}}(\lambda)\frac{h}{\cos\theta}} \tag{1}$$

where $\mu_{\mathrm{a}}(\lambda)$ represents the effective absorption coefficient of the medium, h corresponds to the medium thickness, and θ represents the angle between the ray direction, after being adjusted to account for the detour effect as described next, and the medium's normal direction. If $P(\lambda) < \xi$, where ξ is a random number uniformly distributed in the interval [0..1], then the ray is considered to be absorbed. Otherwise, it is assumed that the ray continues its run through the mesophyll tissue without triggering absorption events.

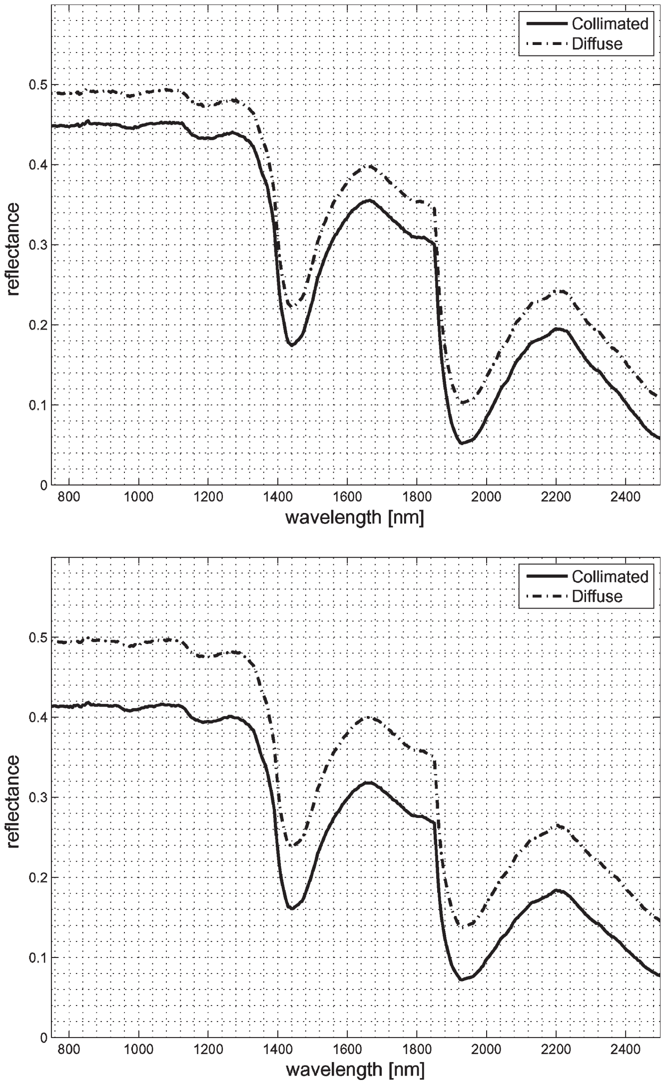

Fig. 1. Modeled reflectance curves for (top) a soybean leaf and (bottom) a corn leaf obtained considering the diffuse and collimated (2.5°) light incident on the specimens' adaxial surface.

We remark that the direction of propagation of a ray traveling in the mesophyll tissue can be altered due to geometrical scattering caused by tissue structures larger than the wavelength of the light. In the ABM-B and ABM-U, this deviation is represented by the angle θ_{s} between the medium's normal direction and the ray's altered trajectory, which in turn is obtained by perturbing its direction of propagation using a warping function that takes into account the aspect ratio of the medium's cells [24]. Note that regardless of the magnitude of θ_{s}, it is assumed that it is probabilistically possible that the ray goes through the mesophyll tissue without triggering the absorption events, i.e.,

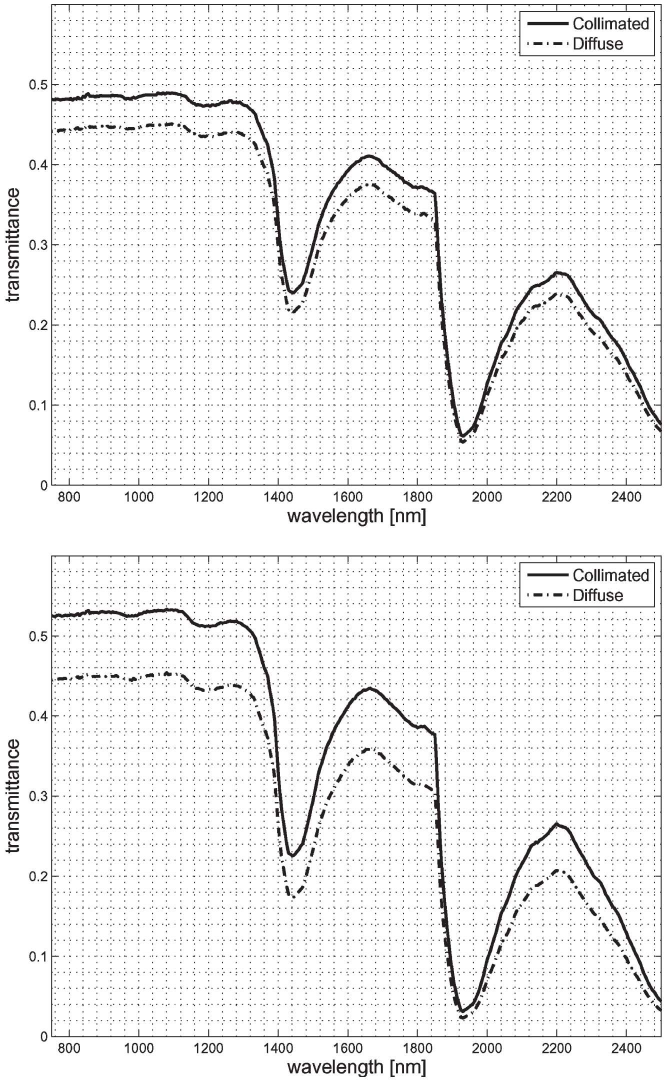

Fig. 2. Modeled transmittance curves for (top) a soybean leaf and (bottom) a corn leaf obtained considering the diffuse and collimated (2.5°) light incident on the specimens' adaxial surface.

the sieve effect is independent of the geometrical scattering. This assumption is consistent with the general theory of sieve effect [14], [29].

From photometric experiments on bifacial and unifacial plant leaves reported in the literature [10], [13], it can be observed that as the angle between the medium's normal and the direction of propagation of the light traveling in the mesophyll tissue increases, the photon flux decreases, i.e., there is a noticeable increase in the medium's absorption efficiency (due to the detour effect). Conversely, as the angle decreases, the photon flux increases, i.e., there is a noticeable decrease in the absorption efficiency (due to the sieve effect). This aspect illustrates not only that detour and sieve effects may be inversely related as suggested by their opposite dependence on the distribution of the absorbers but also that this relationship may be correlated with the angular distribution of the rays traveling in the mesophyll tissue.

It is important to note that the previously cited measurements were performed for a selected number of wavelengths (below 750 nm). It is assumed, however, that the qualitative observations related to the spatial distribution of the propagated photons can be extended to the investigated spectral domain. This assumption is supported by studies performed by Seyfried *et al.* [30] involving plant tissue spectrophotometric measurements from 350 to 1000 nm. These studies indicated that incident collimated light quickly becomes diffuse when it penetrates the foliar tissues, and although the geometrical path length is small for small angles of penetration, the optical path length is large. Furthermore, experiments by Okada *et al.* [31] on the estimation of the optical-path length of collimated light propagating at 800 nm in inhomogeneous tissues provide an upper bound for the angular deviation due to light interaction with absorbers. This bound was also incorporated in the procedural simulation of sieve and detour effects. It corresponds to approximately 1 rad for phantoms (objects resembling organic materials in mass, composition, and dimensions, which are used in biomedical investigations on the absorption of radiation within living tissues) with absorptive and scattering characteristics similar to plant tissue compounds.

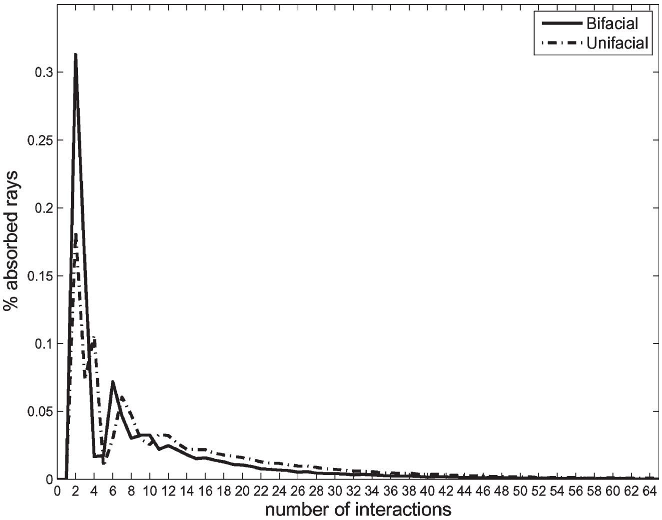

Fig. 3. Number of interactions that rays traveling at 1000 nm have to go through before being absorbed within the bifacial (soybean) and unifacial (corn) specimens' mesophyll tissue. Measurements were performed considering an angle of incidence of 2.5°.

In order to account for the inverse angular relationship between the sieve and detour effects described previously and to avoid undue complexity, the ABM-B and ABM-U make use of a simple formula to obtain θ. According to this formula, the value of θ in radians corresponds to the cosine of θ_s, i.e., the higher the angle θ_s, the lower is the angle θ (between 0 and 1 rad) and, consequently, the lower is the probability of absorption (1).

III. EXPERIMENTS AND DISCUSSION

Quantitative comparisons performed by Baranoski [24] showed good quantitative agreement between the measured data and the modeled results provided by the ABM-B and ABM-U. This suggests that the accuracy of the procedural simulation of foliar sieve and detour (implemented in those models and qualitatively examined in this paper) is within acceptable limits since the modeled spectral curves (reflectance and

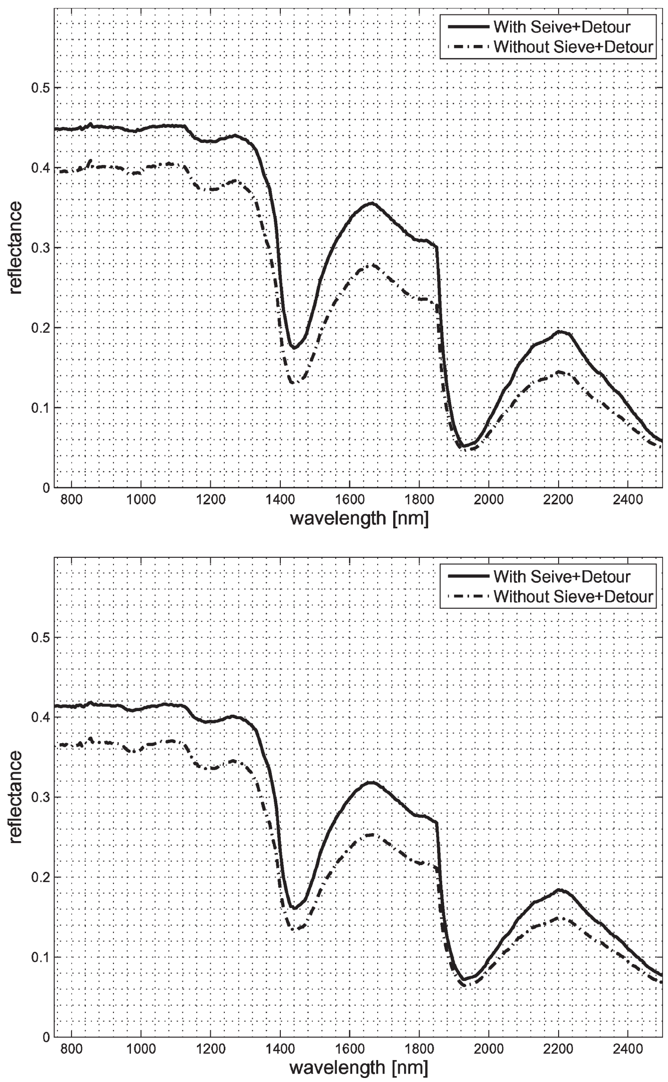

Fig. 4. Modeled reflectance curves for (top) a soybean leaf and (bottom) a corn leaf obtained with and without the procedural simulation of sieve and detour effects. Measurements were performed considering the collimated light (2.5°) incident on the specimens' adaxial surface.

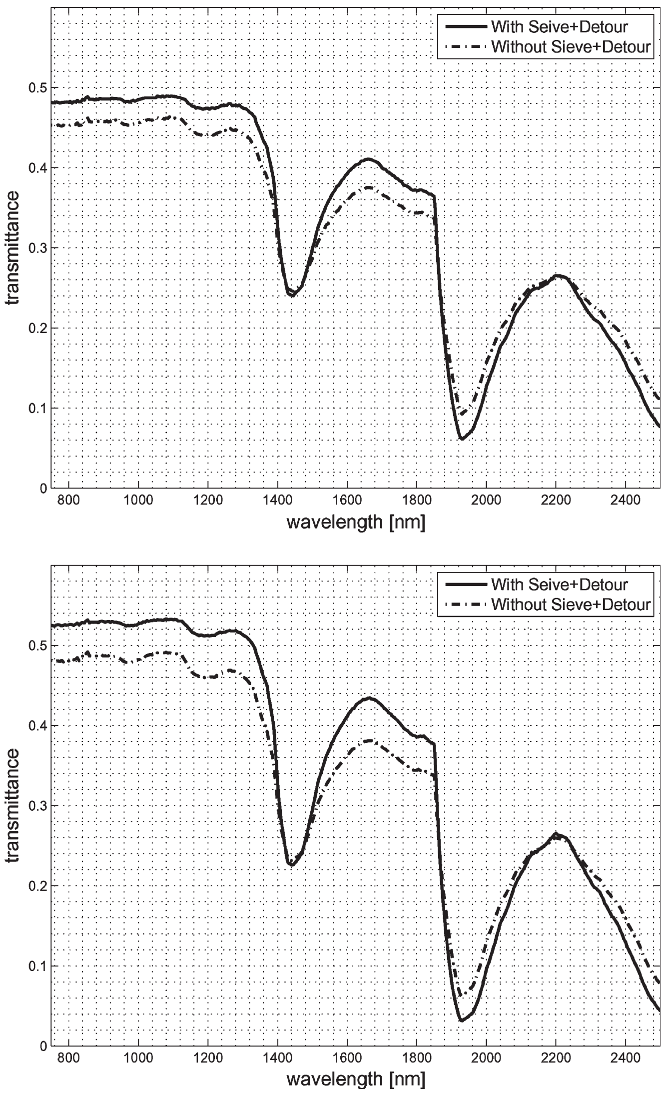

Fig. 5. Modeled transmittance curves for (top) a soybean leaf and (bottom) a corn leaf obtained with and without the procedural simulation of sieve and detour effects. Measurements were performed considering the collimated light (2.5°) incident on the specimens' adaxial surface.

transmittance) presented root-mean-square errors smaller than 0.03, which indicates good spectrum reconstruction according to Jacquemoud *et al.* [32]. Although data scarcity prevents a more comprehensive quantitative analysis of these simulations, their effects on the predictability of the modeled results are further examined in this section with respect to the relationship between the directional quality of the incident light (collimated or diffuse) and the differences in leaf anatomy (bifacial or unifacial). For these experiments, we selected a bifacial dicotyledon soybean leaf and a monocotyledon unifacial corn leaf and used the same characterization data (model input data describing the modeled specimens' biophysical characteristics such as thickness and water content) provided by Baranoski [24].

In order to facilitate the qualitative comparison of the modeled results with observations reported in the literature, the modeled corn specimen's thickness was changed to have the same value used for the soybean specimen, namely 0.0166 cm. This value represents a 20% reduction in its original thickness which is accompanied by a 20% increase in the aspect ratio of its epidermal and mesophyllic cell caps [24], [25]. We also remark that both models take into account the same number of optical interfaces (six), and we used the same refractive indexes for the cutinized epidermal cell wall of both specimens [24].

Spectrophotometric measurements performed by Walter-Shea *et al.* [33] on corn and soybean leaves (considering directional light incident on the adaxial surface of these specimens) show that as the angle incidence with respect to the leafs' normal increases, the reflectance of light by monocotyledon (corn) and dicotyledon (soybean) specimens increases, and the transmittance decreases. Since diffuse incident light includes photons from all directions, i.e., small and large angles of incidence, one can expect higher reflectance values for both specimens when the diffuse incident light is employed and higher transmittance values when the specimens are illuminated by the collimated light. As can be observed in the graphs shown in Figs. 1 and 2, which were obtained considering the diffuse and collimated (2.5°) incident light, the simulations succeeded in predicting these spectral variations with respect to the

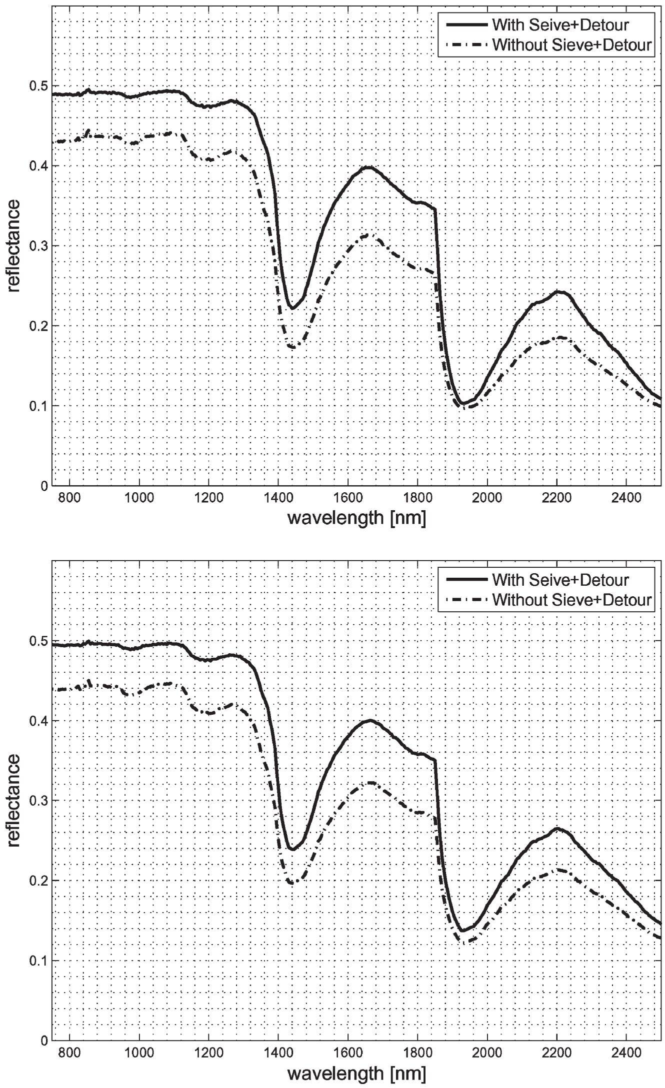

Fig. 6. Modeled reflectance curves for (top) a soybean leaf and (bottom) a corn leaf obtained with and without the procedural simulation of sieve and detour effects. Measurements were performed considering the diffuse light incident on the specimens' adaxial surface.

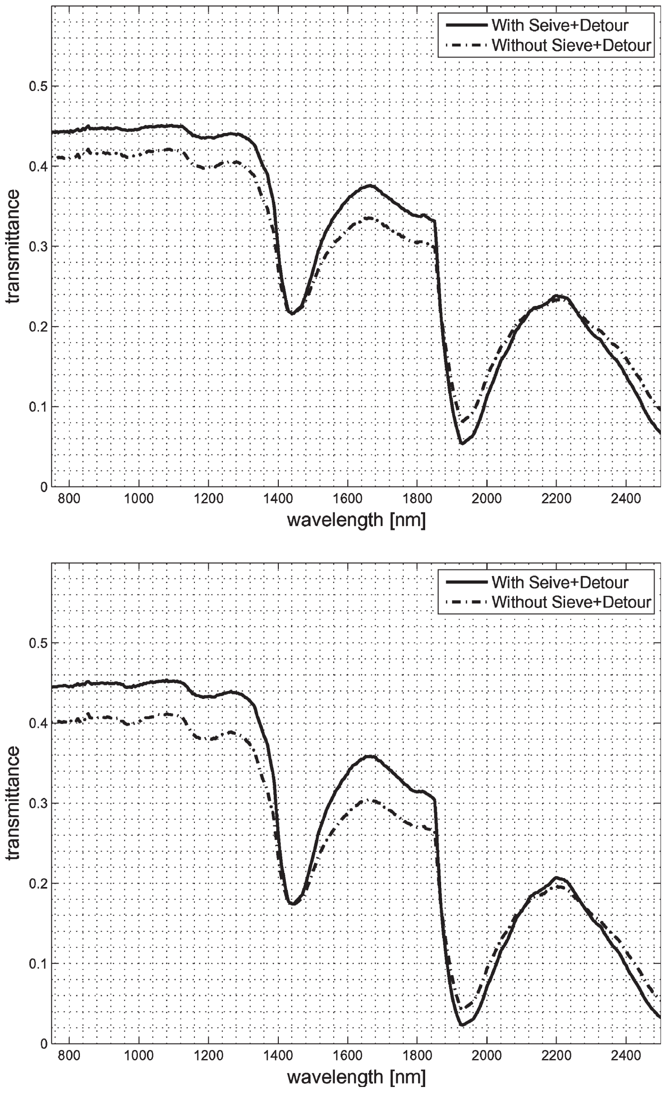

Fig. 7. Modeled transmittance curves for (top) a soybean leaf and (bottom) a corn leaf obtained with and without the procedural simulation of sieve and detour effects. Measurements were performed considering the diffuse light incident on the specimens' adaxial surface.

directionality of the incident light. Furthermore, according to Verdebout *et al.* [21], for the same thickness, monocotyledons whose mesophyll cells are more uniformly distributed have a lower near-infrared reflectance and a higher near-infrared transmittance than dicotyledons which have a palisade and spongy mesophyll. This statement was also confirmed by the spectrophotometric reflectance and transmittance measurements performed by Walter-Shea *et al.* [33]. The stochastic simulations described previously can also predict this behavior as illustrated by the modeled reflectance and transmittance curves for the directional (collimated) incident light shown in Figs. 1 and 2, respectively.

These spectral variations have been explained in terms of the more lacunous structure of the dicotyledon leaf, which allows for greater amount of geometrical scattering [21], [34]. According to the studies by Vogelmann and Björn [6] on the light-trapping role of these cavities, the various optical boundaries within the foliar tissues control the penetration and distribution of light within these tissues, and can cause photons to bounce back and forth between the different tissue layers before being either absorbed or propagated back to the environment. Accordingly, in the ABM-B and ABM-U, a ray may also interact a few times with the different foliar optical interfaces. The graphs shown in Fig. 3 illustrate the pattern of interactions that collimated rays at 1000 nm exhibited before being absorbed within the bifacial (soybean) and unifacial (corn) specimens' mesophyll tissue. As can be observed in these graphs, although a large proportion of the absorbed rays stop after two interactions, i.e., after starting their first run in the mesophyll tissue, the number of interactions decreases asymptotically as expected from an optical system prone to a certain degree of light trapping.

As observed by several researchers [4], [11], [13], [14], [17], sieve and detour effects have a direct impact on the visible light attenuation processes that take place within the plant leaves and affect their spectral signatures in this domain. The modeled curves shown in Figs. 4–7 suggest that a similar premise may be valid for the investigated spectral domain since, without properly accounting for the relationship between sieve and detour effects [e.g., using θ equal θ_s in (1)], there is a noticeable quantitative difference in the results provided by the ABM-B and ABM-U. In addition, the modeled curves shown in Figs. 4–7 also indicate that the net result of the procedural simulation of sieve and detour effects is a reduction of absorption efficiency for most part of the investigated spectral domain. This reduction may be explained by the highly heterogeneous distribution of absorbers interacting with radiation in the investigated spectral domain [14].

IV. CONCLUDING REMARKS

The relationship between attenuation processes, the directionality of the incident light, the internal arrangement of the tissues, and sieve and detour effects has been fairly well documented for applications involving the visible domain. However, as mentioned earlier, reports addressing this relationship in the infrared domain are scarce in the literature. For this reason, certain aspects observed in the visible domain could not be incorporated in the procedural simulation of sieve and detour effects in the infrared domain (in the range of 750–2500 nm). For example, in studies involving the visible domain, it was observed that variations in the optical path length have a wavelength dependence, and they are also correlated to the absorbers' concentration [17]. Clearly, there is a lack of quantitative evidence to confirm these dependences with respect to compounds that attenuate light in the investigated spectral domain. Viewed in this context, this paper also aims to highlight the need for actual measured data to support further research on the interaction of infrared radiation with plant leaves. However, we believe that this circumstantial scarcity of data should not prevent investigations in this area. After all, oftentimes, theories and hypotheses are the required catalysts to fundamental experimental research [35].

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