Reflections on the Brilliance of ASPEN TREES

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Each fall, the aspen trees in the high country of the Rocky Mountains put on a spectacular show that draws visitors from "the flatlands" in droves. During the spring and summer months, aspens have a rather undistinguished green appearance, but as summer turns to fall, the accompanying cool temperatures cause the leaves to undergo a remarkable change. When the temperature dips low enough to curtail production of chlorophyll, but not low enough to freeze the leaves and cause them to turn black, they take on colors that range from pale to brilliant yellow, depending on lighting and the viewing angle.

The authors observed that the yellow aspen trees seemed to have a more brilliant appearance when they were back-lighted (or in other words, when the viewer was looking toward the sun with the trees in between) than when they were front-lighted (sun at the viewer's back, with the viewer between the sun and the trees). A detailed study of this observation was conducted during the fall of 2000 and 2001, when the authors took field trips into the mountains near Vail, Colorado, to collect data. The photographs of Fig. 1, taken about two hours before sunset on a clear day, illustrate the difference in the appearance of the trees in the presence of front- and back-lighting. The photograph on the left, which has a pale yellow overall appearance, is of a front-lighted tree; in contrast, the photograph on the right, which has a more brilliant yellow appearance, is of that same tree with back-lighting.

Model of an aspen tree

For all practical purposes, an aspen tree may be considered an ensemble of leaves. Aspen leaves are somewhat oval in shape. They are attached by flexible stems to small limbs that are, in turn, attached to the tree's main branches. Because of the extreme flexibility of the stems, the slightest breeze

Figure 1. Photographs of an aspen tree with front-lighting (*left*) and back-lighting (*right*).

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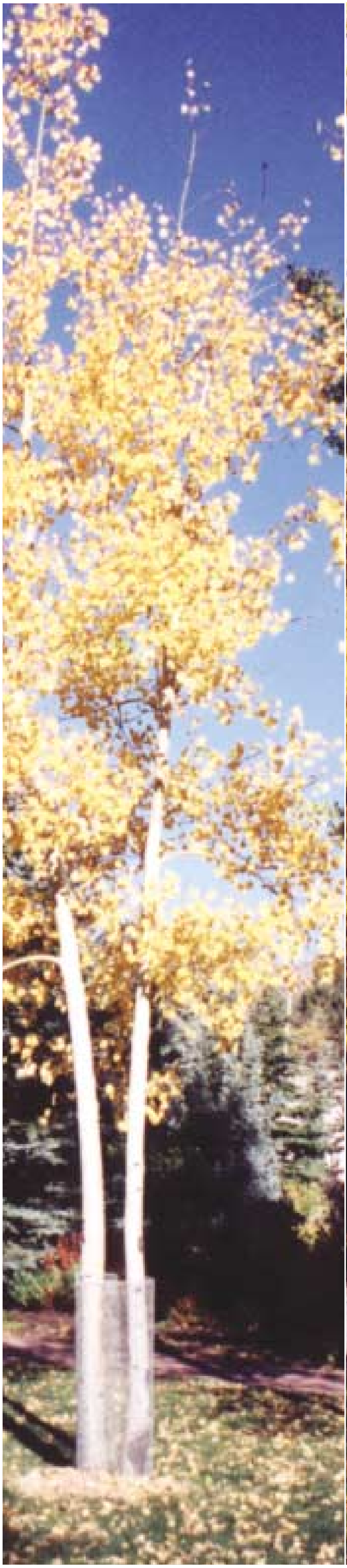

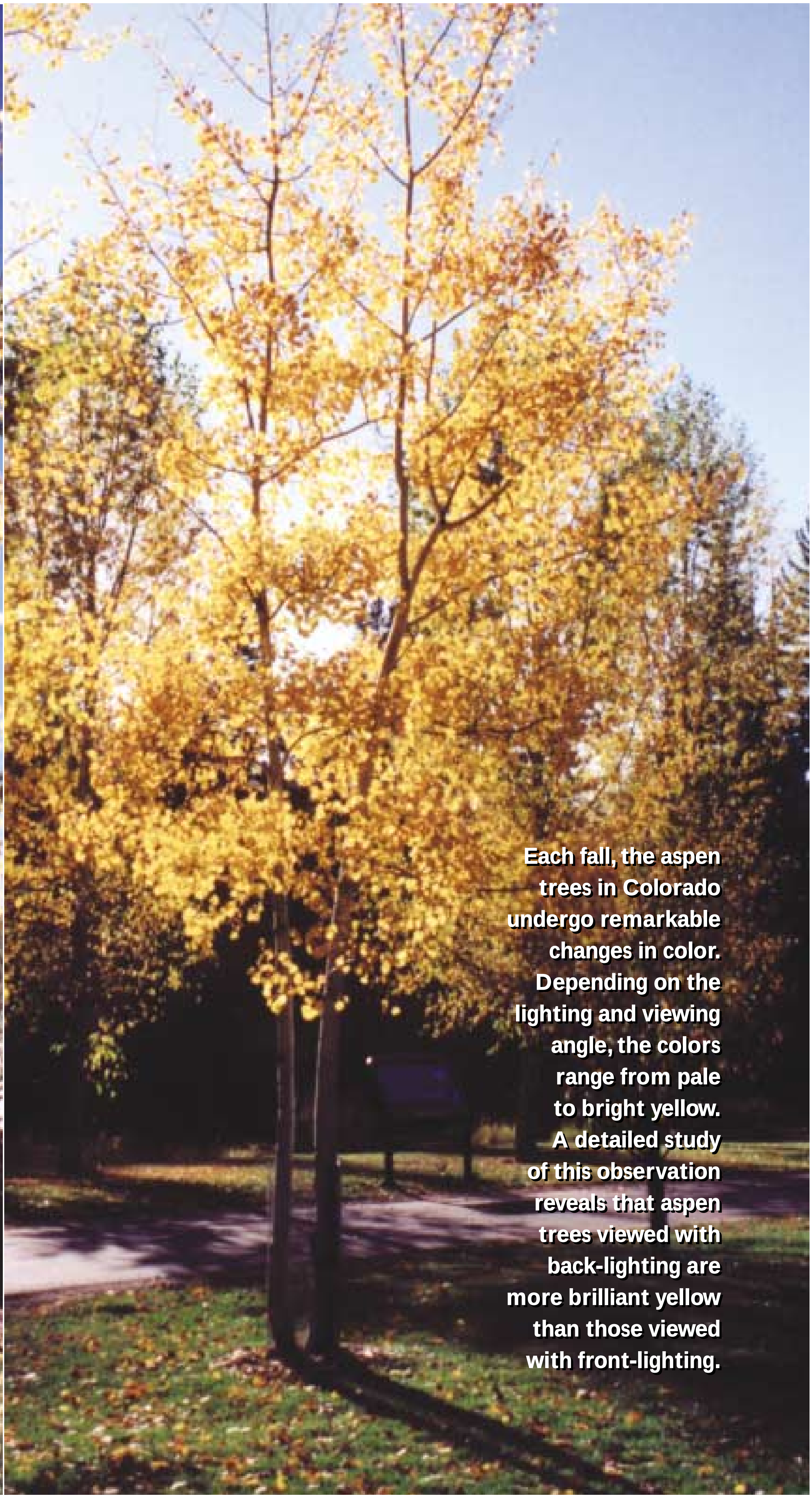

Each fall, the aspen trees in Colorado undergo remarkable changes in color. Depending on the lighting and viewing angle, the colors range from pale to bright yellow. A detailed study of this observation reveals that aspen trees viewed with back-lighting are more brilliant yellow than those viewed with front-lighting.

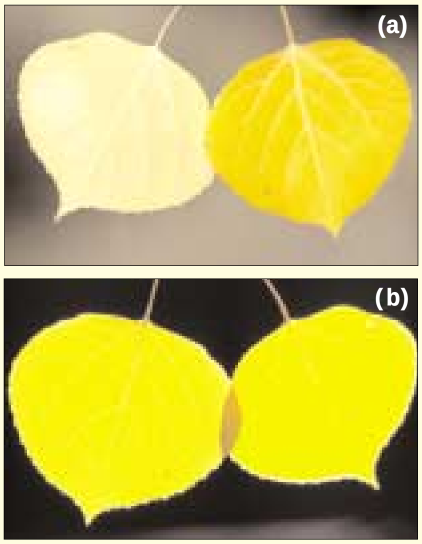

Figure 2. Appearance of aspen leaves, (a) front-lighting; (b) back-lighting.

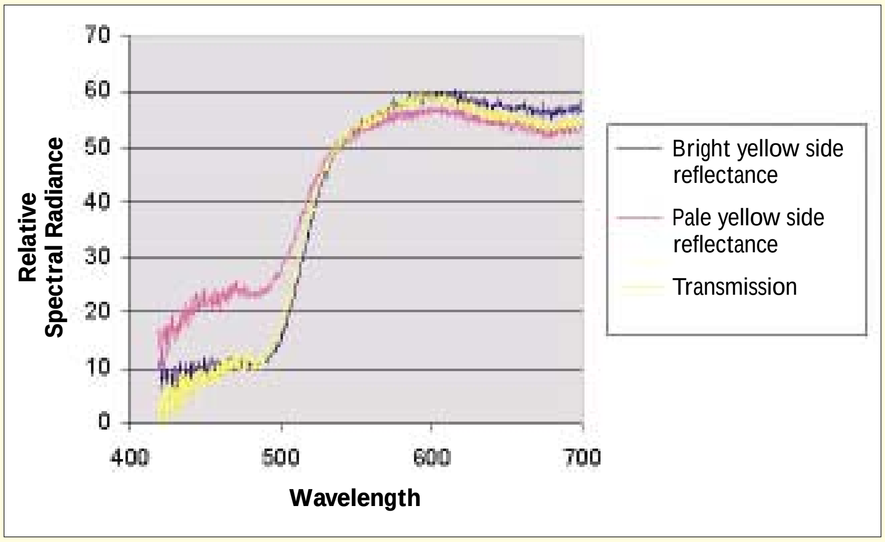

Figure 3. Spectral reflectance and transmittance of aspen leaf.

causes the leaves to flutter noticeably, thus giving rise to the name "quaking aspen." As there appears to be no tendency for the leaves to be oriented preferentially, it seems reasonable to assume their orientation is quite random. For this reason it is equally likely either side of a leaf will be seen by an observer. The ease with which a light breeze causes the leaves to flutter should only serve to introduce further randomization of their orientation.

For purposes of discussion, we shall refer to the two sides of an aspen leaf as "side A" and "side B." Of those leaves viewed by an observer, approximately half will be oriented with side A visible at any instant in time, and half with side B visible. Thus, over a reasonable interval of observation, a person should effectively be presented with an ensemble-average view of the leaves, half of which will be oriented with side A visible, and half of which will be oriented with side B visible.

The appearance of aspen leaves

When an aspen leaf is observed with front-lighting, there is a significant difference in the appearance of side A and side B, as illustrated in Fig. 2(a). The light reflected from side A yields a brilliant yellow color (right), while the light reflected from side B results in a pale yellow color (left). This suggests that the spectral content of the light reflected by the two sides is significantly different. In contrast, when a leaf is viewed with back-lighting, as illustrated in Fig. 2(b), the brilliance of side A (left) is nearly the same as that of side B (right). This suggests that the light transmitted by the leaves is spectrally similar, irrespective of their orientation relative to the observer. Furthermore, the brilliance of the transmitted light for either of these orientations is nearly the same as that of the light reflected by side A in the presence of front-lighting.

Laboratory measurements

To understand the appearance of the leaves, we made spectral-reflectance and spectral-transmittance measurements of several aspen leaves using a spectrometer and a tungsten light source. The spectral characteristic of the tungsten source was removed from the measurements. To allow us to compare the shape of all three curves, the transmittance curve was normalized to the mean value of the reflectance curves at 600 nm. Figure 3 shows that there is a significant difference between the reflectance of the pale yellow side and the reflectance of the brilliant yellow side from 425-525 nm. The brilliant yellow side has about one-half the reflectance of the pale yellow side within this wavelength region. In addition, the spectral transmittance curve of the leaf has nearly the same shape as the spectral reflectance curve of the brilliant yellow side of the leaf. Other aspen leaves were measured and showed very similar results. These measurements corroborate the visual impression that the spectral reflectance from the brilliant yellow side of an aspen leaf closely matches the spectral transmittance of the leaf.

Conclusions

When a yellow aspen tree is viewed with back-lighting, the ensemble-average of the transmitted light is represented by a single spectral distribution because the spectral characteristics of the light transmitted by the leaves are the same irrespective of their orientation relative to the observer. Thus, the overall appearance of the trees is one of brilliant yellow. However, when that tree is viewed with front-lighting, the ensemble-average of the reflected light contains two significantly different spectral distributions: one, associated with reflection from side A of the leaves, displays the same brilliant yellow characteristic as that of the transmitted light in back-lighting; the other, associated with reflection from side B, displays a pale yellow characteristic. Thus, the overall brilliance of the tree is diminished by the existence of the pale yellow component of the light reflected from side B of the leaves. As a result, aspen trees viewed in back-lighting appear to be a more brilliant yellow than those viewed in front-lighting.

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