

Previsual Detection of Two Conifer-Infesting Adelgid Species in North American Forests

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Abstract

The balsam woolly adelgid, *Adelges piceae*, and hemlock woolly adelgid, *A. tsugae* (Homoptera: Adelgidae), are invasive pests of coniferous forests in both the Eastern and Western United States. Balsam woolly adelgid is capable of attacking and killing native North American firs, with Fraser fir (*Abies fraseri* (Pursh) Poir.) in the East and subalpine fir (*A. lasiocarpa* (Hook.) Nutt.) in the West being particularly susceptible to infestation. Hemlock woolly adelgid is capable of infesting native hemlocks and is a serious pest in forests of the Eastern United States where it is causing significant mortality to both eastern (*Tsuga canadensis* (L.) Carr.) and Carolina hemlock (*T. caroliniana* Engelm.). Infestations by either of these insects may take several years to kill the host tree. Damage by hemlock woolly adelgid frequently causes needles to discolor from deep green to grayish green. Discoloration of needles is also one of the symptoms used to diagnose infestations of balsam woolly adelgid. Traditional methods for assessing damage by these adelgid species include field surveys and aerial detection surveys. However, because infestations frequently occur in remote locations and can take years to build up, stand damage may accrue prior to visual detection of the infestations. Branch-level, spectral data of the foliage from trees were collected for several categories of infestation. In the Western United States, data were collected from subalpine fir infested with balsam woolly adelgid in northern

Idaho. In the Eastern United States, data were collected from eastern hemlock in western North Carolina. Trees were sampled using a hand-held spectroradiometer. The measured radiance spectra were converted to percentage of reflectance and comparisons made between the infestation categories. Separation of the infestation levels occurred in a progressive pattern moving from noninfested to newly (or lightly) infested to heavily infested trees. Results suggest that previsual detection of this group of invasive insects may be possible with appropriate spatial and spectral sensor resolution.

Keywords: Host resistance, hyperspectral, insect detection, multispectral, remote sensing.

Invasive Adelgids in North American Conifers

Adelgids (Homoptera: Adelgidae) are small insects with piercing and sucking mouth parts. They have a white woolly covering that is secreted over the body. There are several native adelgid species within North America such as the Cooley spruce gall adelgid (*Adelges cooleyi*), and some of these can cause growth loss in trees or cause trees to reach economic injury levels under some conditions. However, the two adelgid species that are currently causing the most economic and ecological impacts within North America are the introduced balsam woolly adelgid (*A. piceae*) and the hemlock woolly adelgid (*A. tsugae*), both of which are established in both the Eastern and Western United States.

Balsam Woolly Adelgid: Hosts and Biology

Balsam woolly adelgid is native to the fir forests of central Europe and was introduced into the United States around 1900. The life cycle of the balsam woolly adelgid consists of the egg, three larval instars, and the adult (see Hain 1988 for a more thorough description). The only life stage capable of movement is the first instar larva (termed the crawler) that, upon locating a suitable feeding site, inserts its stylet into the bark and transforms (without molting) into a nonmobile phase, after which the insect is permanently attached to the host tree. As the female feeds, she secretes a dense woolly covering that ultimately covers the entire insect.

The crawler stage does not have wings, and between-tree dispersal is a passive process. The adult female produces as many as 248 eggs. These are oviposited within the woolly mass, which acts to protect all of the life stages except the crawler.

All of the true firs (*Abies*) that are native to North America show some degree of susceptibility to the balsam woolly adelgid (Mitchell 1966). The susceptibility ranges from slight for noble fir (*A. procera* Rehd.) and white fir (*A. concolor* (Gord. & Glend.) Lindl. ex Hildebr) to moderate for grand fir (*A. grandis* Dougl. ex D. Don) Lindl., cork-bark fir (*A. lasiocarpa* var. *arizonica* (Merriam) Lemm.), and Shasta red fir (*A. magnifica* var. *shastensis* Lemm.) to severe for subalpine fir (*A. lasiocarpa* (Hook.) Nutt.), Fraser fir (*A. fraseri* (Pursh) Poir.), balsam fir (*A. balsamea* (L.) Mill.), and Pacific silver fir (*A. amabilis* Dougl. ex Forbes). The insect is established on susceptible hosts in the Eastern and Western United States where it is responsible for significant levels of mortality in some stands. Prior studies suggest that there may be some connection between host monoterpenes and attack success by balsam woolly adelgid (Arthur and Hain 1987).

Hemlock Woolly Adelgid: Hosts and Biology

Hemlock woolly adelgid is native to Asia and was first reported in the Pacific Northwest in the 1920s. The adelgid was reported in Eastern North America in the 1950s and Connecticut in the 1980s. The insect is now present in many of the hemlock forests of the Eastern United States, where infestations frequently result in significant mortality to native hemlocks (Souto and others 1995). The hemlock woolly adelgid is a serious pest of Eastern hemlocks and represents a significant threat to the sustainability of native hemlocks (*Tsuga canadensis* (L.) Carr. and *T. caroliniana* Engelm) in the Eastern United States (McClure 1992). Whereas the adelgid is also established in the Western States, it does not appear to be a threat to the western hemlock species (*T. heterophylla* (Raf.) Sarg. and *T. mertensiana* (Bong.) Carr.) at the present time.

Hemlock woolly adelgid has two generations per year in much of its range in the Eastern United States. Only females are present, and the spring generation lays between

100 and 300 eggs. Upon hatching, the crawlers search for suitable feeding sites, insert their stylets and begin to feed. As with balsam woolly adelgid, crawlers become immobile once they settle and begin to feed. When the crawlers reach maturity, two types of adults can form. One type of adult has wings and dies as it searches for the alternate spruce host, which is not present in North America. The other is wingless and capable of laying eggs to produce the next generation.

Conifer Resistance to Insect Attack

There are several hypotheses regarding plant resistance to insect attack that involve the production and allocation of resources within the plant as they relate to the plant's resistance mechanisms. The carbon: nutrient balance hypothesis correlates the production of plant secondary metabolites that are important in determining the relative resistance/susceptibility of the plant with the ratio of carbon to other nutrients within the plant (see Herms and Mattson 1992). The growth differentiation balance hypothesis also views changes in the production and maintenance of plant secondary metabolites as a tradeoff owing to environmental constraints on growth and secondary metabolism (i.e., differentiation) (see Herms and Mattson 1992). The growth differentiation balance hypothesis predicts that under moderate stress, plant growth will be limited, and the production of secondary metabolites such as those important in insect resistance will increase.

Conifer Resistance to Insect Attack: Generalized Response Sequence

Conifer resistance to stem-invading insects has received much attention and involves a generalized, three-step sequence of wound cleansing, infection containment, and wound healing (Berryman 1972, Hain and others 1983). The first step of this response, wound cleansing, is characterized by the production and flow of constitutive resins. The second step of the resistance sequence, infection containment, can be described as a rapid necrosis of cells surrounding the infection site that is accompanied by the development of traumatic resin ducts and an increased concentration of monoterpenes and phenolics in the reaction zone (Cook

and Hain 1986, Raffa and Berryman 1982, Reid and others 1967). The accumulation of terpenes and phenolics in the reaction zone is also accompanied by a decrease in the level of soluble sugars in that zone (Cook and Hain 1986, Wong and Berryman 1977). Wound healing, or formation of wound periderm, is the final step of the resistance sequence. This isolates the wound from the rest of the tree. Wound periderm is located adjacent to the necrotic tissue and protects living tissue from the adverse effects of the dead cells in the necrotic zone surrounding the attack site(s) (Mullick 1977). The three-step resistance sequence requires an expenditure of energy by the tree, and there is typically a resulting change of color (fading) within the tree's foliage.

Fir Response to Stem Attack by the Balsam Woolly Adelgid—

The impact of balsam woolly adelgid infestation on North American firs has been studied extensively over the past several decades. Infestation by the adelgid results in anatomical and structural changes within host tissues that may be the result of salivary excretions from the insect's stylet during feeding. Physically, the xylem tissue of infested trees has higher concentrations of ray tissue (Mitchell 1967, Smith 1967), thickened cell walls, and shorter tracheids (Doerksen and Mitchell 1965). The tracheids have encrusted pit membranes that more closely resemble the pit membranes associated with heartwood (Puritch and Johnson 1971). There is a corresponding reduction in waterflow in infested trees (Mitchell 1967) that puts the tree into a state of physiological drought; this, in turn, reduces photosynthesis and respiration (Puritch 1973) and can ultimately result in tree death.

The damage to the host tree is related to both the size of the tree and the intensity of the infestation. Balsam woolly adelgid infestations in the crown of a tree usually result in gouting of the outer branches (characterized by node or bud swelling or both with a decrease in new growth of the stem and foliage) (Mitchell 1966). Over time, the crown thins, and the foliage fades in color. Balsam woolly adelgid infestations also occur on the stems of trees. In North America, these stem infestations usually kill native firs within 6 years (Hain 1988).

Hemlock Resistance to Attack by Hemlock Woolly Adelgid—

Once hemlock woolly adelgid settles onto a twig, the tree usually suffers needle loss and bud mortality, followed by branch and whole tree mortality (usually within 6 years) (McClure 1991, Shields and others 1995). Foliar chemistry appears to play some role in host susceptibility/resistance to hemlock woolly adelgid, with resistance being related to foliar levels of calcium, potassium (K), nitrogen (N), and phosphorous (Pontius and others, 2006). These authors suggest that higher levels of N and K in the foliage enhance host palatability and, thus, result in increases in the population levels of hemlock woolly adelgid. In addition, soil and foliar chemistry along with landscape position can be used to model hemlock susceptibility to Hemlock Woolly Adelgid (Pontius and others 2009). These hypothesized relationships between foliar chemistry and infestation could be important for early detection of hemlock woolly adelgid infestations because some foliar constituents such as chlorophyll, N, cellulose, and sugar can be accurately estimated using spectral data (Curran and others 2001).

As with other conifers, monoterpenes are major constituents of tree chemistry of hemlocks (i.e., Li and others 2001). These compounds may function in several ways to mediate the interaction between trees and herbivores, but one impact is that they are frequently toxic to attacking insects such as bark beetles (i.e., Cook and Hain 1988) or other arthropods such as spider mites (i.e., Cook 1992). It has been suggested that the monoterpene content of western hemlocks may function as a deterrent to hemlock woolly adelgid (Lagalante and Montgomery 2003). The authors suggest that elevated levels α -pinene, β -caryophyllene, and α -humulene may act as feeding deterrents against hemlock woolly adelgid, and that elevated levels of isobornyl acetate may attract the adelgid.

Importance of Previsual Detection

Minimizing the elapsed time between when a tree becomes infested with an insect and when that infestation is detected can increase the treatment options available to forest managers. Detection of an infestation prior to when the foliage begins to visibly fade should give managers more

time to respond. Active resistance mechanisms by a host tree to insect attack can be energy intensive to maintain and utilize. The decline that occurs within a host following infestation by adelgids may be categorized into various levels as characterized for hemlock infested with hemlock woolly adelgid (Pontius and others 2005) or balsam fir infested with balsam woolly adelgid (Luther and Carroll 1999). Changes in foliar chemistry that are related to tree stress can be manifested in measurable spectral changes within the foliage. Much of the literature with regard to another tree-killing insect, mountain pine beetle (*Dendroctonus ponderosae*), is reviewed by Wulder and others (2006). The review suggests that remotely sensed data is useful for detecting infestations of mountain pine beetle damage and that future experimental work be conducted at several spatial scales.

Spectral Data

Both the spatial resolution (i.e., pixel size) and spectral resolution (the width of the individual spectral wavebands over which plant response is measured) of spectral data, as well as the overall wavelength range examined (some sensors operate through the middle infrared region, some do not), can influence the ability to detect infested trees. Multispectral remotely sensed data types tend to have fewer, wider spectral wavebands and are operationally available from satellite platforms over a wide range of spatial resolution (< 1 to 30 m). Landscape-scale hyperspectral data are less widely available and have a large number of very narrow wavebands. Because most available data sets are acquired from aircraft platforms, these data tend to have spatial resolution on the order of 6 to 20 m. Handheld spectroradiometers with wavelength widths and numbers similar to hyperspectral sensors are often employed in the field and laboratory to study spectral response of canopy components.

Prior Attempts to Use Spectral Imagery to Detect or Delineate Adelgid Infestations

There have been several prior studies related to the detection and classification of trees infested with invasive adelgids. Luther and Carroll (1999) examined several

foliar indices for assessing stress in balsam fir using spectral reflectance data and reported that foliar reflectance decreased consistently with vigor. These authors conducted their work in the laboratory using a fixed-position spectroradiometer. Adelgid infestation was not specifically investigated, but infestation of fir with balsam woolly adelgid does result in tree stress (see Hain 1988). At the landscape scale, hemlock stands were similarly assessed and analyzed for health status using multispectral Landsat Thematic Mapper data (Bonneau and others 1999). The best overall accuracy for classifying stand health based on hemlock woolly adelgid infestation was obtained using the Modified Soil Adjusted Vegetation Index-2. Pontius and others (2005) used hyperspectral data to examine the abundance and early decline of hemlock infested with hemlock woolly adelgid. These authors suggest that wavelengths in the low end of the spectral range may be useful in assessing early stages of decline of hemlock infested with hemlock woolly adelgid. One purpose of our ongoing research is to determine if host decline resulting from infestation by invasive adelgids in multiple tree genera can be evaluated by using similar spectra among the host genera.

Comparison of Hyperspectral Data for the Previsual Detection of Balsam Woolly Adelgid and Hemlock Woolly Adelgid Infestations

Our studies have used hyperspectral data collected at the branch level. Spectral data were collected using a Geophysical Environmental Research Corp. 2600 handheld spectroradiometer with a spectral resolution of 1.5 nm from 350 nm to 1050 nm and a resolution of 11.5 nm from 1050 nm to 2500 nm. In the case of balsam woolly adelgid, we have concentrated on subalpine fir, the primary host of this insect in Idaho. Our studies of hemlock woolly adelgid have concentrated on its primary host in western North Carolina, *Tsuga canadensis*. For both insect-tree pairs, spectral data were collected from trees in various stages of infestation. Five branches were cut from each tree that was examined. Branches were cut from various heights and orientations throughout the canopy of the trees. The branches and foliage were placed on a flat black surface with negligible amounts of measurable radiation, and five measurements per tree

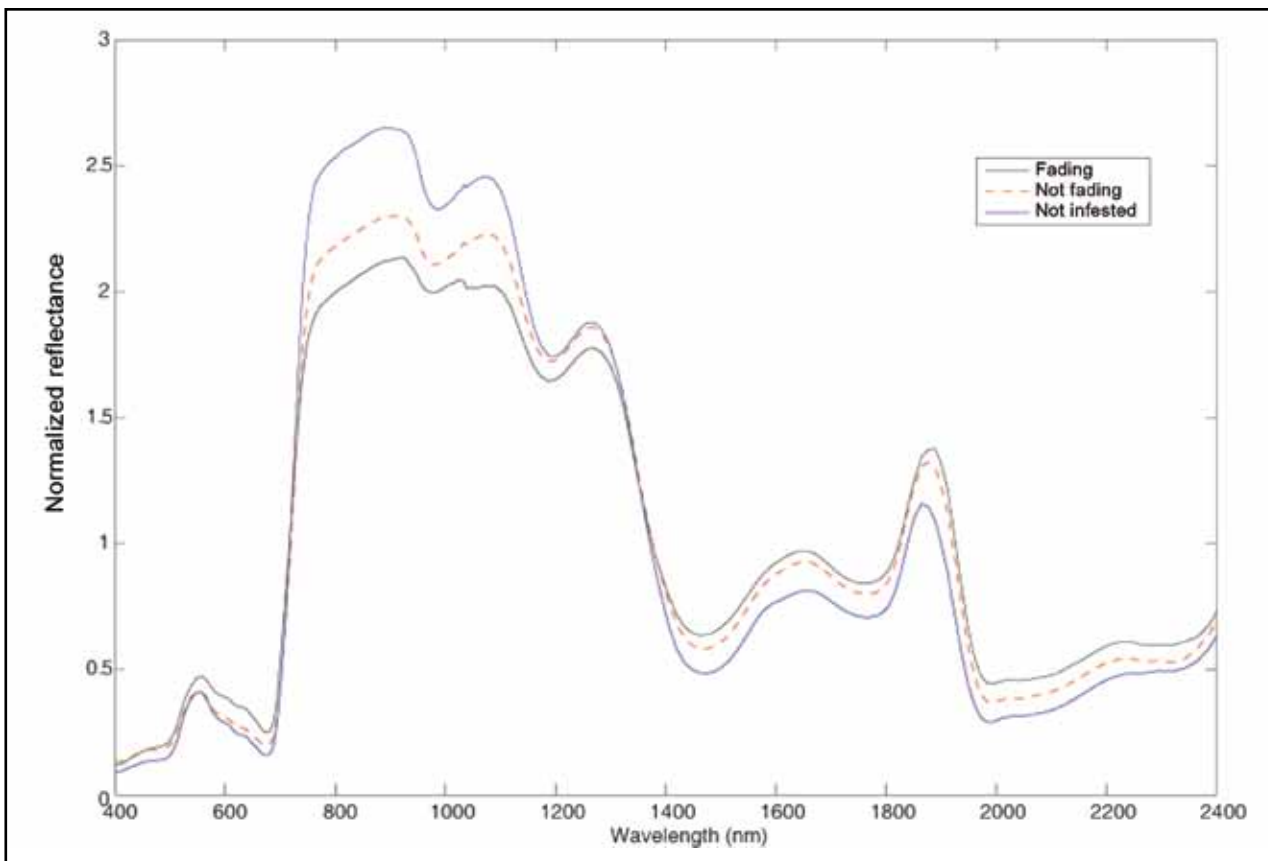


Figure 1—Spectral measurements of subalpine firs, *Abies lasiocarpa*, in Idaho with three levels of infestation with balsam woolly adelgid, *Adelges piceae*. The infestation categories are not infested = blue, infested but with no visible symptoms = red, and infested with visible symptoms = black.

were obtained in an iterative manner, with the foliage being rearranged between each measurement. The radiometer was placed at a height of approximately 50 cm above the branch samples, and measurements were made when the sun angle was within 10° of solar noon. The spectra for these five replicates of branch measurements were averaged to obtain a measure of each tree's reflectance properties. The data for each tree were smoothed using a weighted moving filter, and comparisons were made of the spectral response among infestation classes.

In Idaho, subalpine firs in three infestation categories were sampled. The categories included trees that had no current infestation with balsam woolly adelgid, trees that were infested with balsam woolly adelgid but had no apparent crown fading, and trees that were infested with balsam woolly adelgid and had visible signs of this infestation.

Using Analysis of Variance procedures and the SAS statistical analysis package, significant differences were found among the three infestation categories for some wavelength regions. Our results demonstrated a consistent response in the normalized spectral reflectance curve of subalpine fir, stressed by infestation of balsam woolly adelgid, across the reflectance spectrum shown in Figure 1. More specifically, there is an increased reflectance in the visible region of the reflectance curve (< 700 nm), decreased reflectance in the Near Infra Red plateau (centered around 1000 nm), and increased reflectance in the shortwave infrared region (beginning around 1450 nm) as visual decline becomes apparent. The overall changes in spectra are similar to those reported for other stresses in balsam fir (Luther and Carroll 1999). Multispectral aerial imagery (Landsat and SPOT data) was also collected for areas with active balsam woolly adelgid infestations. Because of the relatively

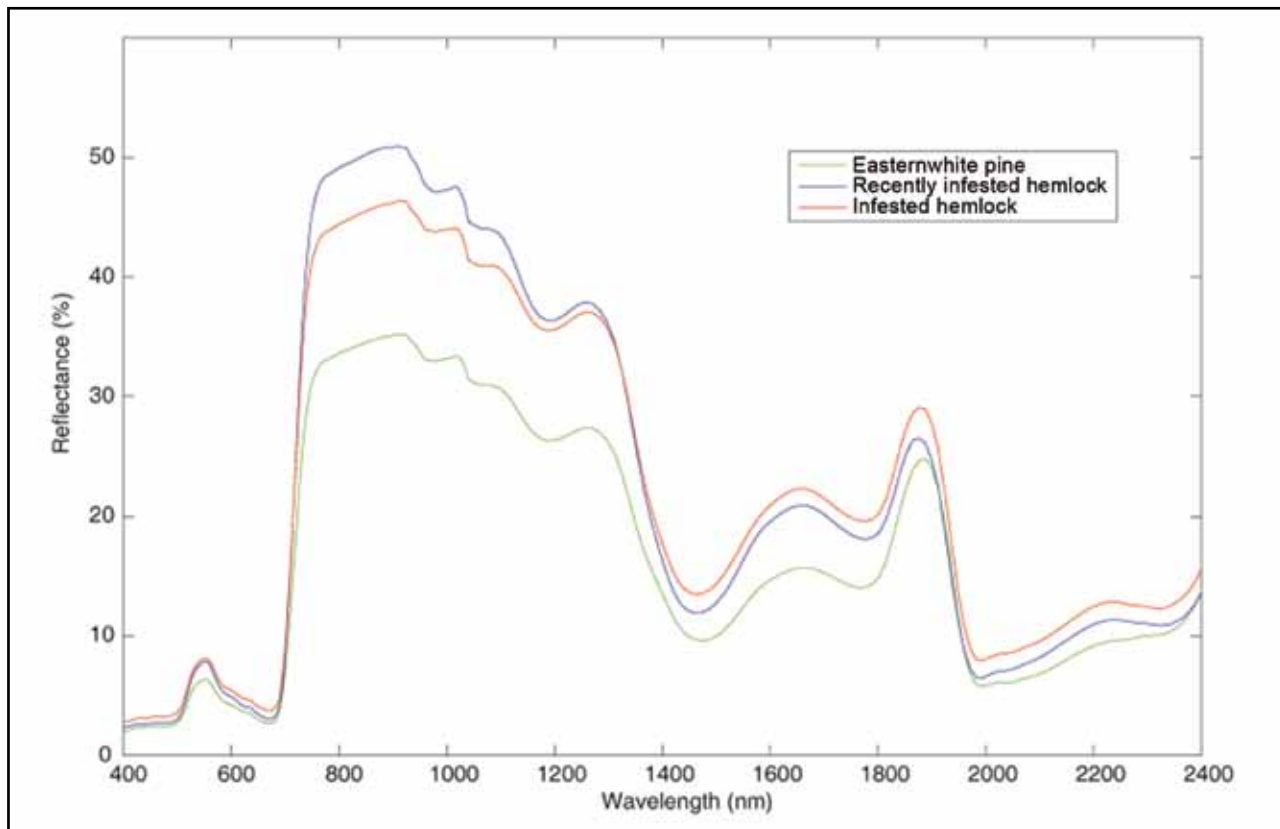


Figure 2—Spectral measurements of eastern white pine, *Pinus strobus*, and eastern hemlocks, *Tsuga canadensis*, in North Carolina with two levels of infestation with hemlock woolly adelgid, *Adelges tsugae*. The spectral categories are eastern white pine = green, recently infested but with no visible symptoms = blue, and infested with visible symptoms = red.

narrow canopy architecture of subalpine fir and the patchy distribution of the species in the areas of data collection, no conclusive results were obtained.

In North Carolina, hemlock trees that were recently infested (within the past year) or that had been infested for multiple years were sampled as was eastern white pine (*Pinus strobus* L.) (the only other conifer present within the stands that we sampled) during June of 2005. No uninfested stands of hemlock were found within the study areas. There were visible differences in the overall spectral measurements between the hemlocks that were recently infested with hemlock woolly adelgid and those that had been infested for a longer period of time (Figure 2). The spectral signature of eastern white pine, the only other conifer present within the stands that could be confused with the hemlocks, differed significantly from both categories of infested hemlock within the stands (Figure 2). The pattern

of decreased spectral values with increasing stress is similar to the decreases measured in subalpine fir infested with balsam woolly adelgid in the Near Infa Red plateau and increases again in the shortwave Infa Red region (Figure 1). The ability to distinguish declining hemlock at the branch level also supports the prior landscape-level investigations of Pontius and others (2005), but larger data sets from a variety of geographic locations are still needed.

Implications for Detection and Delineation of Forest Insect Infestations

The branch-level spectral data for both tree species infested with their specific invasive adelgids were both consistent and in general agreement with the shoot-level spectral changes of balsam fir under various stresses that were measured under laboratory conditions (Luther and Carroll 1999). The measurements were also in general agreement with the results of Pontius and others (2005) who examined

hemlock woolly adelgid at the landscape level. Therefore, the spectral changes that occur with stress are measurable at several scales. The combined results of these studies suggest that spectral data may aid in developing a tool for previsual detection and monitoring of forest decline associated with these adelgid species. However, limitations do exist. One of the primary limitations may be the ability to separate different stressing agents or factors.

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