

Developing and Validating a Method for Monitoring and Tracking Changes in Southern Pine Beetle Hazard at the Landscape Level

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Abstract

The objective of this research project is to develop and validate a method for using satellite images and digital geospatial data to map the distribution of southern pine beetle (SPB) habitats across the pinelands of east Texas. Our approach builds on a work that used photo interpretation and discriminant analysis to identify and evaluate environmental conditions suitable for SPB infestation. Because current implementations of Billings and Bryant's method by the Texas Forest Service (TFS) use manual photo interpretation, they are relatively costly, labor intensive, and require sampling. Satellite imagery and geographic information system (GIS) technology present potential means to reduce operational costs and improve accuracy. Here we report the principal results of our work in a pilot area of east Texas, specifically: (1) development and integration of satellite and digital inputs into the Billings and Bryant model, (2) accuracy assessment of model inputs, (3) validation of the model adaptation through comparison of satellite-derived SPB hazard maps to operational maps produced by TFS, and (4) revalidation of the model through comparison of satellite-derived SPB hazard maps to known locations of SPB infestations. Collectively, the results point to the considerable potential of satellite imagery and automated analysis techniques to produce timely, accurate, and cost-effective maps of SPB hazard at the landscape level.

Keywords: *Dendroctonus frontalis*, GIS, hazard rating, remote sensing, risk assessment, satellite data, Texas.

Introduction and Background

The southern pine beetle (SPB), *Dendroctonus frontalis* (Coleoptera: Curculionidae: Scolytidae), is one of the most destructive insect pests of pine forests in the Southern United States, Mexico, and Central America (Thatcher and others 1980). The beetle's range extends from New Jersey to Texas and from New Mexico and Arizona to Nicaragua. Because populations build rapidly during periodic outbreaks and large numbers of trees are killed, this insect generates more concern among managers of southern pine forests than any other insect pest. In the Southern United States, average annual losses may exceed 100 million board feet of sawtimber and 20 million cubic feet of growing stock (Price and others 1998).

Southern pine beetle outbreaks have increased in frequency, severity, and distribution during the past 30 years. Preventive silvicultural practices offer the most promising and long-lasting means of reversing this trend (Belanger and others 1993, Nebeker and others 1985). If pine stands are weakened by drought, flooding, lightning strikes, careless logging, or overcrowding, they become more susceptible to attack by the beetle (Blanche and others 1983, Hicks and others 1980). Mature trees in pure, dense stands have long been considered most susceptible to SPB attack, but, in recent years, unthinned pine plantations have increasingly supported SPB infestations (Cameron and Billings 1988). Trees less than 5 years of age or less than 4 inches in diameter are seldom attacked. Dense pine stands also are more likely to suffer extensive losses from the expansion of established SPB infestations in the absence of direct control (Hedden and Billings 1979).

The most practical approach to minimizing timber losses and avoiding costly short-term suppression projects is to maintain forests in a vigorous, healthy condition (Belanger 1980, Hedden 1978). To manage SPB populations

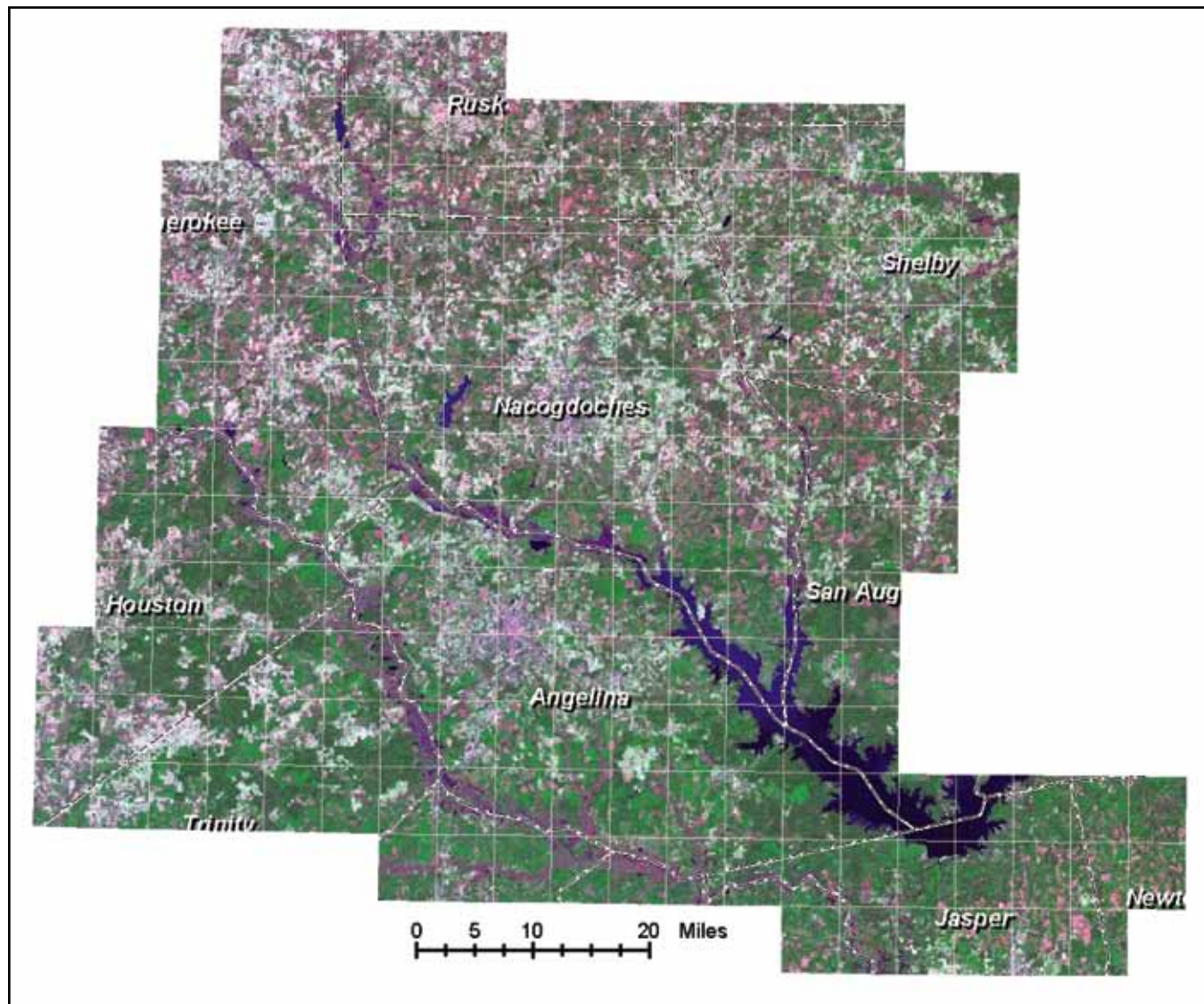


Figure 1—Location of the project area in east Texas. Boundaries of counties and 18,000-acre grid blocks are indicated in white.

more effectively, foresters need reliable means of predicting where infestations are most likely to occur. Once this capability is developed, areas where beetle-caused timber losses are likely can be identified and managed through long-range plans (Peterson 1984), silvicultural manipulations (Belanger and Malac 1980, Belanger and others 1993) or more responsive direct control tactics (Swain and Remion 1981), or all. Several practical stand hazard rating systems have been developed that utilize easily measured stand and site factors (basal area, tree age or height, growth rate in the last 5 years, land form, etc.) to ascertain susceptibility

to SPB at the stand level (Hicks and Mason 1982, Hicks and others 1980, Lorio and others 1982, Mason and others 1985). Identification of SPB hazard at the landscape level, however, has received much less attention.

A system for mapping SPB hazard at the landscape level using aerial photography has been developed and implemented by the Texas Forest Service (TFS) on an 18,000-acre grid (Billings and Bryant 1983, Billings and others 1985). The rating system uses conventional photo-interpretive methods to describe host presence, coverage, density, and site conditions within 30-acre photo plots.

Table 1—Independent variables used in the Billings and Bryant (1983) hazard model

Variable	Description
A	Nonhost (open land, hardwoods, water)
B	Young pine (less than 15 years of age)
C	Pine host, < 70 percent coverage, < 80 percent crown closure, other terrain
D	Pine host, < 70 percent coverage, < 80 percent crown closure, bottomland
E	Pine host, < 70 percent coverage, ≥ 80 percent crown closure, other terrain
F	Pine host, < 70 percent coverage, ≥ 80 percent crown closure, bottomland
G	Pine host, ≥ 70 percent coverage, < 80 percent crown closure, other terrain
H	Pine host, ≥ 70 percent coverage, < 80 percent crown closure, bottomland
I	Pine host, ≥ 70 percent coverage, ≥ 80 percent crown closure, other terrain
J	Pine host, ≥ 70 percent coverage, ≥ 80 percent crown closure, bottomland

Twenty circular photo plots, equally spaced in five rows and four columns, provide a 3-percent systematic sample of host conditions within each grid block.

An initial hazard map for east Texas based on 1981-83 aerial photography covered 656 grid blocks (11,808,000 acres) and was validated using subsequent SPB detection records (Billings and others 1985). In 2003-04, as part of the ongoing SPB prevention project, the east Texas hazard map was updated using 1996 color infrared photography. The updated map identified 16 grid blocks (2 percent) as extreme hazard, 92 (12 percent) as high hazard, 291 (37 percent) as moderate hazard, 280 (35 percent) as low hazard, and 117 (15 percent) as very low hazard.

Although the east Texas hazard maps have been valuable for predicting where SPB outbreaks are most likely to occur and for targeting prevention programs, their production process has three limitations that have prevented widespread adoption of this protocol. These limitations are:

- **Expense:** Creating a SPB hazard map across east Texas (14.3 million acres) requires high resolution color infrared imagery and procedures to digitize and orthorectify the imagery. Furthermore, photo interpretation must be performed by trained technicians. All three requirements are very costly.
- **Accuracy:** Though the aerial imagery is analyzed systematically, the manual interpretation process requires sampling and frequent judgment calls, both of which introduce inaccuracy.

- **Frequency:** Presently, the time and expense of aerial photo collection and interpretation limit the extent and update frequency of SPB hazard maps. If the process were relatively inexpensive and automated, hazard maps could be generated frequently over larger areas.

To address these limitations, the Texas Forest Service (TFS) and Forest One (now Lanworth, Inc.), with the support of the USDA Forest Service Southern Research Station, began a project to investigate the potential of satellite imagery and digital image processing methods to lower the costs and improve the accuracy of the operational east Texas SPB hazard maps. Here we report the principal results of this investigation in a pilot area of east Texas (Figure 1), specifically:

1. Development and integration of satellite and digital inputs into the Billings and Bryant model.
2. Accuracy assessment of the model inputs.
3. Validation of the model adaptation through comparison of satellite-derived SPB hazard maps to operational maps produced by TFS.
4. Revalidation of the model through comparison satellite-derived SPB hazard maps to known locations of SPB infestation.

Methodology

The Billings and Bryant model of SPB hazard takes the form of the discriminant function:

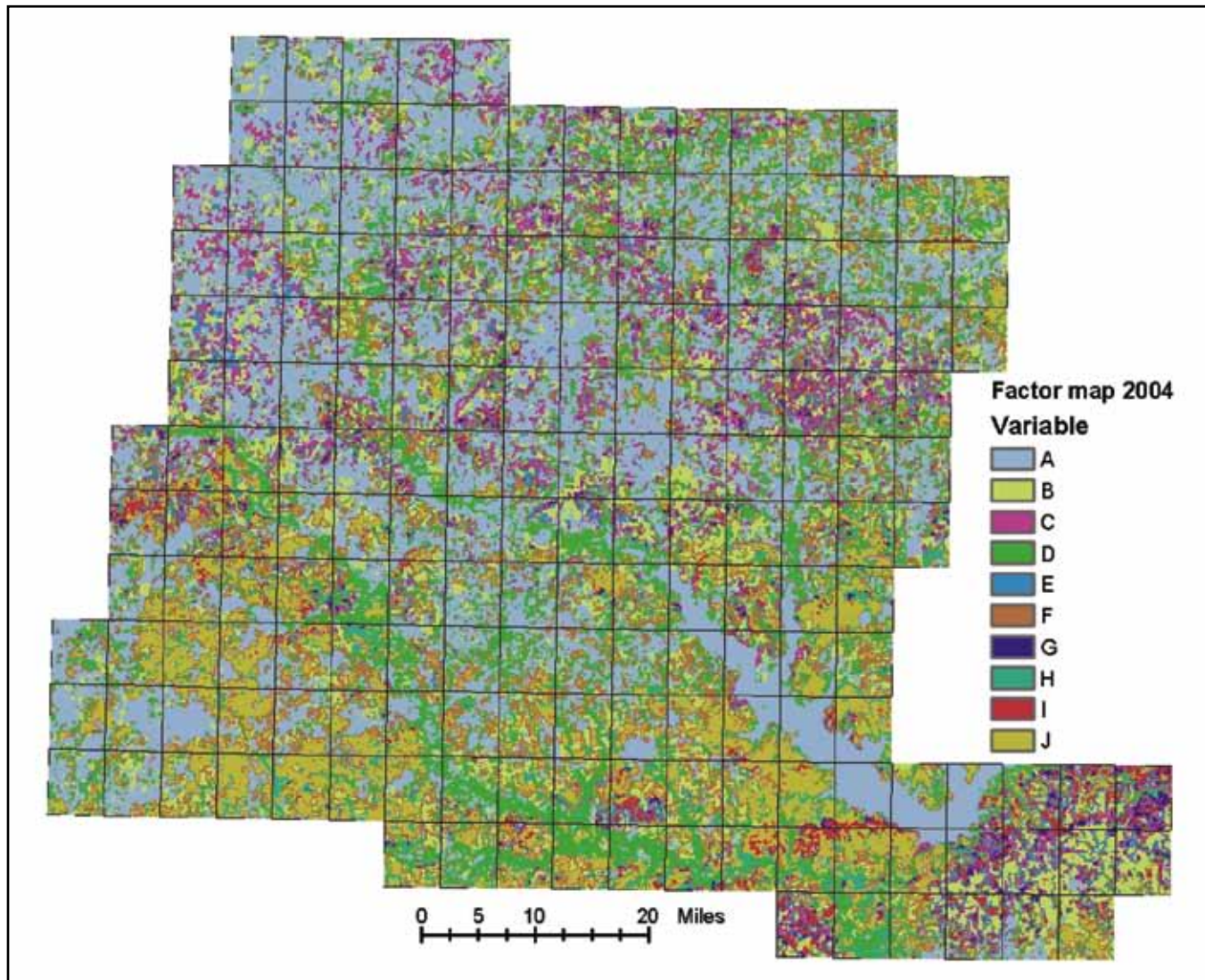


Figure 2—Distribution of hazard factor combinations (habitat types) across the project area (December 2004).

$$DS = -1.35 - 0.108(A) + 0.135(D) + 0.330(E) + 0.404(F) + 0.305(I) + 0.271(J)$$

where the values of the discriminating variables A, D, E, F, I, and J are the numbers of photo plots in a grid block that have the combination of site/stand factors listed in Table 1. Thus, if five photo plots in a given grid block fall on water or agricultural land (factor combination A) and seven others fall on dense, old pine (factor combination I), the values of variables A and I are 5 and 7, respectively. Because only 20 photo plots are analyzed per grid block, the possible value of each variable ranges from 0 to 20. Note, however, that the values of the discriminating variables will not necessarily

sum to 20 as not all site/stand factor combinations appear in the discriminant function.

The challenge of applying satellite data to the determination of SPB hazard at the grid block scale lies in replicating the process of photo interpretation used by TFS without violating the assumptions and conditions of the discriminant function.

The foundation of our approach to SPB hazard mapping is Forest One's Forest Age Map product, a raster map based in Landsat imagery in which each 28-m (30.6 yd) cell (pixel) is classified into one of four forest types (softwood, hardwood, mixed, nonforest) and in which all softwood

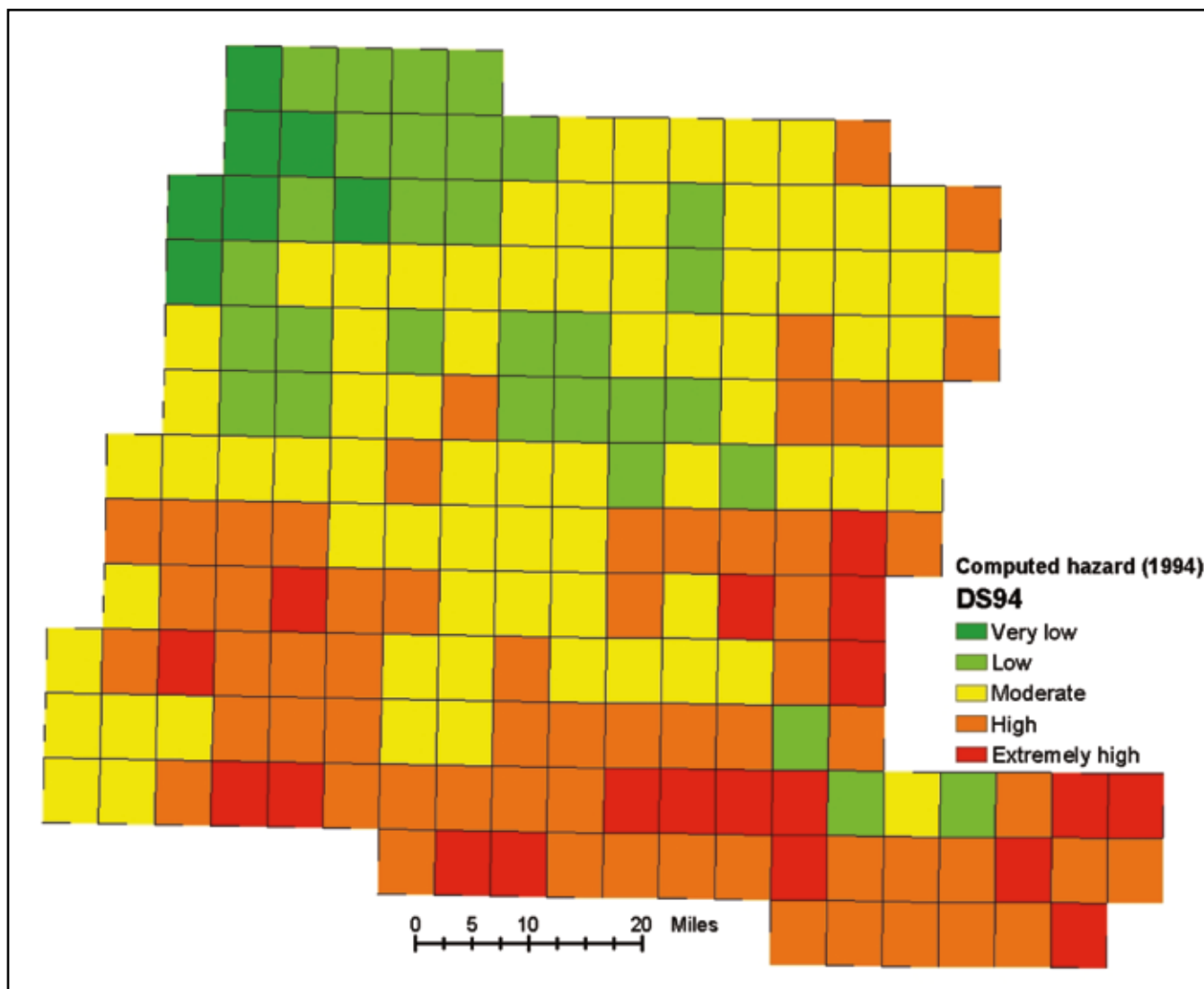


Figure 3—Grid block hazard ratings for 1994 derived from satellite and digital geospatial data.

pixels are further classified into 3-year age classes (e.g., 0 to 3 years, 7 to 10 years, etc.). To develop a SPB host map for the year 2004, Forest One recoded its Forest Age Map, classifying all hardwood, nonforest, and softwood younger than 15 years as nonhost and all softwood older than 15 years as host. To compare satellite-derived SPB hazard to existing TFS hazard maps from 1996 and SPB spot data from 1989 to 1993, Forest One also prepared Forest Age Maps and host maps for 1994 and 1990.

Because the TFS hazard rating protocol considers the percentage of host pine within a 30-acre (12.1 ha) photo plot rather than the predominant host type in a 28-m (30.6

yd) (12.1 ha) pixel, the host maps must be transformed to represent varying percentage of host pine across the study area. This was accomplished by recoding the host maps so that pixels classified as nonhost and young pine have a value of 0, and pixels classified as pine host have a value of 1. A 13 x 13 average filter was then passed over the recoded maps, replacing each pixel by the arithmetic mean of its neighborhood. A 13 x 13 matrix of 28-m (30.6 yd) pixels has an effective area of 32.7 acres (13.2 ha), and the resulting pixel value will therefore estimate the proportion of host pine in a photo plot-sized area centered on each pixel.

Table 2—Comparison of satellite (Forest One 1994) and photo-interpreted (TFS 1996) hazard class predictions. Agreement within 1 hazard class is 89 percent

Texas Forest Service hazard class	F1 hazard class					Total	
	Extreme	High	Moderate	Low	Very low		
	Extreme	4	1	0	4	0	5
	High	5	11	9	5	0	30
	Moderate	5	13	16	27	5	66
	Low	1	5	13	41	21	81
	Very low	0	0	0	7	1	8
Total	15	30	38	80	27	190	

	N	Percent
Agreement	73	38 percent
F1 underestimate (1 class)	58	31 percent
F1 overestimate (1 class)	38	20 percent
Disagreement	21	11 percent

As a further qualification of site/stand conditions, the TFS hazard rating protocol measures host density as a function of canopy closure in areas of each plot containing host pine. As a proxy for host density, we selected a vegetation index computed from the red, near-infrared, and midinfrared bands of Landsat TM imagery acquired in 1990, 1996, and 2004. The vegetation index, called NDVIc, uses the distinctively high reflectance of green vegetation in the near-infrared wavelengths relative to the red and middle-infrared wavelengths to map the relative distribution of green biomass across the project area. Furthermore, because soils tend to reflect strongly in the middle-infrared wavelengths, middle-infrared reflectance is negatively correlated with canopy closure. NDVIc is a unitless quantity that varies between -1 and 1. To restrict this measurement to areas of host pine, the host maps were used to assign null values to areas of young pine and nonhost. A 13 x 13 average filter was then passed over the NDVIc maps to estimate for each

pixel the average density of host pine in a photo plot-sized area centered on that pixel.

Current TFS protocol distinguishes between pine stands with less than 80 percent canopy closure and those with 80 percentage of closure or greater. To determine the actual relationship between NDVIc and percentage of canopy closure, we partitioned several 1-m color-infrared digital orthophoto quarter quadrangles from 1995 into canopy and noncanopy pixels. We then computed the proportion of 1-m (39.4 in) canopy pixels present within the area covered by each 28-m (30.6 yd) pixel from a 1994 Landsat image. The average NDVIc value of all Landsat pixels containing more than 80 percent crown elements (NDVIc = 0.425) was then selected as the threshold for 80 percent canopy closure.

The final site/stand factor considered under the TFS protocol is landform, expressed as bottomland or other terrain. To determine the landform most characteristic of the photo plot-sized area centered on each 28-m pixel within the

Table 3—Observed rates of SPB^a infestation (1991-93) by satellite-predicted hazard class (1990)

Hazard class	New spots (1991-93)	N Grid blocks	Infestation rate (spots/class/grid block)
Extreme	159	15	10.60
High	409	28	14.61
Moderate	652	58	11.24
Low	583	81	7.20
Very low	21	8	2.63

^a SPB = Southern pine beetle.

study area, the National Elevation Data set digital terrain model was resampled to match the grid resolution of the Forest Age Map. Percentage of slope was then computed for each grid cell, and a 13 x 13 average filter was passed over both the slope and elevation maps. Based on conversations with photo interpreters at TFS, bottomland was operationally defined as those areas having an average elevation less than 90 m (98.4 yd) and an average slope less than 3 percent.

Once all relevant site/site-stand factors were estimated using remotely sensed inputs, a series of rules was used to assign each pixel to 1 of the 10 factor combinations expected by the Billings and Bryant model (Figure 2). Once a site/stand factor combination was assigned to each 28-m grid cell, the percentage coverage of each factor combination was computed for each of the 190 grid blocks in the study area. This percentage value was then multiplied by 0.2 to scale percentage cover to the 0 to 20 range expected by the discriminant function. The discriminant score was then computed for each grid block for the years 1990, 1994, and 2004, and scores were assigned to hazard classes based on breakpoints used in the 2003-04 TFS update. The satellite-derived hazard map for 1994 is shown as Figure 3.

Accuracy of Model Inputs

To determine the accuracy of the satellite-derived inputs, we compared our maps of host type and coverage to reference data on managed pine stands of known age. The reference data were distributed widely across the project area and constitute a 5-percent sample by area. Analysis shows that Forest One's Forest Age Map classifies pine with at

least 80 percent accuracy and can distinguish between pine greater than 15 years and pine younger than 15 years with 82 percent accuracy. We also compared our measurements of crown closure and landform to operational photo-interpreted measurements made by TFS technicians and found similar levels of agreement. Our conclusion, therefore, is that the satellite-derived inputs into the model are sound.

Comparison of Satellite-Derived and TFS Hazard Maps

The principal result of our work so far has been SPB hazard maps for 1990, 1994, and 2004. The accuracy of the 2004 map is currently being assessed through comparison to operational measurements of hazard factors by TFS. The accuracy of the 1994 map has been assessed through comparison to the 1996 hazard map produced by TFS (Table 2).

The comparison shows that the 1994 map correctly predicted the hazard rating of 38 percent of the grid blocks. The maps predicted a further 51 percent of the grid blocks within 1 hazard rating class. Given some uncertainty about the accuracy of the TFS reference map, we propose to treat all agreements within 1 hazard class as correct predictions and offer 89 percent as the final accuracy of the satellite-derived hazard map. In general, the satellite-derived map tends to underpredict hazard ratings slightly. Forest One and TFS are working to explain and improve the correspondence between the two hazard rating systems.

Comparison of Satellite-Derived Maps and Historic SPB Infestation Data

As a further check on the accuracy of the satellite-derived hazard map and the validity of the underlying discriminant function, TFS supplied data on the location of SPB infestations within the study area during the years 1989-93. These data were organized as SPB infestation counts for each 15-arc second grid block within the study area. To compare these data to the 1990 satellite-derived hazard map, we selected all 15-arc second grid blocks that were infested in 1991, 1992, or 1993 but not in 1989 or 1990. This allowed us to create a map of new infestations since 1990. These infestations were presumably related to landscape conditions

represented by the 1990 satellite map rather than to lingering or renewed infestations from prior years.

To allow comparison of new infestations to satellite-predicted hazard class in 1990, we aggregated all new infestations to the 18,000-acre grid block level and summarized these counts by hazard class (Table 3). Because the area (number of grid blocks) of each hazard class is not constant over the study area, we divided the count of new infestations by the number of grid blocks in each hazard class that were either newly infested in 1991-93 or were not infested at all. This normalized measure was interpreted as the average infestation rate for each hazard class.

Our results reveal a qualitatively strong, positive correlation between the observed infestation rate and the model-predicted hazard class. The mean rate of SPB infestation declined from nearly 15 infestations/grid block in the high hazard class to fewer than 3 infestations per grid block in the very low hazard class. The only observed anomaly is that the infestation rate is slightly lower than expected for the extreme hazard class, perhaps indicating limited resolving power of either the satellite data or the underlying model. This anomaly is currently being investigated by Forest One and TFS.

Conclusions

From the investigations and analyses reported here, we conclude that satellite imagery, together with ancillary digital geospatial data and automated processing techniques, presents a powerful and cost-effective tool for operational mapping of SPB infestation hazard at the landscape scale.

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