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forest management

Comprehensive Methods for Earlier Detection and Monitoring of Forest Decline

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Forested ecosystems are threatened by invasive pests, pathogens, and unusual climatic events brought about by climate change. Earlier detection of incipient forest health problems and a quantitatively rigorous assessment method is increasingly important. Here, we describe a method that is adaptable across tree species and stress agents and practical for use in the field. This approach relies on: (1) measurements covering a range of forest decline symptoms, from early decline to imminent death, (2) normalization of each measurement within each species' natural range, and (3) combining normalized measurements into one summary decline rating, thus creating a rigorous, detailed assessment of forest condition within the context of the species' typical characteristics. We demonstrate the utility of this approach in comparison to traditional field assessments of forest condition for both early detection and more sensitive monitoring over time. This comprehensive approach will allow researchers and forest managers to track subtle changes in tree condition over shorter periods of time, an imperative advancement for the detection and monitoring of invasive pests. While the case studies presented here are based on specific tree species and stress agents, this approach is scalable and broadly applicable to other tree species and stressors, making it a valuable approach for forest health monitoring and assessment.

Keywords: data reduction, data standardization, data summary, forest monitoring, forest pest detection, forest stress, tree health, vegetation condition

During the last several decades, temperate forests in the United States have been subjected to several serious outbreaks of insects and diseases that threaten the existence of their host tree species. In the northeastern United States, this list includes hemlock woolly adelgid (HWA), *Adelges tsugae*; Asian longhorned beetle (ALB), *Anoplophora glabripennis*; and emerald ash borer (EAB), *Agrilus planipennis* (Fairmaire), to name a few. Stress from extreme weather events, possibly linked to climate change, have also impacted forest health across the region, from winter injury in red spruce (Lazarus et al. 2004) to late frost (Payette et al. 1996) in northern hardwoods.

In the case of introduced pests, impacts on forest condition are typically not detected using traditional assessment methods until the stand has been infested for considerable time (Poland and McCullough 2006). In contrast, while climate-induced injury is apparent in conjunction with the stress event, longer-term impacts or recovery response rates are difficult to differentiate using traditional methods. Successful management of forests must include a universal stress detection strategy that results in earlier detection and more sensitive differentiation of physiological stress in trees.

Traditional forest health assessments tend to focus on survivability statistics and tree mortality (Nowak et al. 1990, Wyckoff and Clark 2002, van Mantgem et al. 2009, Lu and Svendsen 2011, Roman and Scatena 2011). The advantage is that it is relatively easy to determine whether a tree is alive or dead. In addition, this information plays a key role in forest management from the standpoint of knowing where salvage or planting activities need to occur.

More recently, the focus has shifted toward assessments of canopy condition into broad vigor categories, or other ocular metrics of relative dieback, defoliation, or discoloration (Cooke et al. 1996, USDA Forest Service 2004, Hallett et al. 2006). These methods go a long way toward the goal of earlier detection of forest health issues and can often lead land managers to problem areas in time to develop mitigation strategies before mortality occurs. In addition, these methods are a key component of scientific studies that are aimed at determining subtle causes of stress such as nutrient depletion or acid deposition (McNulty and Aber 1993, Bailey et al. 2004).

While each of these individual metric provides a useful assessment of forest condition, they primarily capture extreme differences in canopy condition with little differentiation between healthy trees and those demonstrating early decline symptoms. To realize the goal of earlier detection of new threats, monitor subtle changes in stress symptoms over short time periods, predict, and track the spread of symptoms, the following assessment goals must be met:

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1. Consideration of a range of stress symptoms, including "pre-visual" physiological stress response.
2. Adaptability to the various ways tree species manifest stress symptoms and/or respond to various stressors.
3. Calculation of a rigorous and consistent rating system that takes into account all variables and represents all phases of tree health, ranging from ideal condition to mortality.

The goal of this paper is to outline a new, comprehensive approach to forest decline assessments, designed to quantify tree and forest health at a relatively fine scale. While we suggest several field metrics that are likely useful across applications, the selection of key variables is only one part of this comprehensive approach. Equally important is the standardization of each field metric based on the species-specific range of stress characteristics and the combination of multiple stress response variables, regardless of what those variables may be, into one summary decline rating. This flexibility in field metric selection and species-based normalization makes this approach easily adaptable across tree species, scales, and stress agents.

Methods

Because stress symptoms can manifest themselves in many ways, depending on species, severity and nature of the stressor, and the length of time a tree has been under stress, it is useful to quantify several of the symptoms a tree might exhibit over the course of stress exposure. To this end, we suggest several field metrics that have proven efficient in our previous forest health assessments efforts. This includes stress response symptoms ranging from early/incipient decline to symptoms of impending mortality. To maximize the detail and accuracy of decline assessments, here, we describe several options that minimize subjective, ocular measurements. However, we encourage the inclusion or substitution of any variables that may help characterize forest condition specific to study goals, tree species, or stress agent.

Photosynthetic Capacity (Previsual Stress Response)

Physiologically, one of the earliest and most subtle signs of stress is a reduction in net photosynthesis. This can be directly measured as chlorophyll fluorescence (a measure of photosynthetic activity), chlorophyll content (quantity of photosynthetic apparatus), or canopy productivity (e.g., amount of new growth in conifers) (Carter and Knapp 2001). The most efficient way to assess this early reduction in photosynthetic capacity following stress exposure in the field is with fluorometers (Mohammed et al. 1995) such as the Handy PEA Chlorophyll Fluorescence meter (Hansatech Instruments 2001). We have found that five leaves selected from the healthiest, upper and outer canopy are sufficient to assess and compare the photosynthetic capacity of tree canopies. Leaves are clipped for 30 minutes of dark adaptation then saturated with high intensity light from the sensor light-emitting diode. By measuring chlorophyll fluorescence induction kinetics following photosystem saturation (Strasser and Tsimilli-Michael 2001), the Handy PEA calculates a set of fluorescence indices to quantify photosynthetic activity. The Performance Index (PI) (Hermans et al. 2003) is a probability index based on this response curve that has been linked to the efficiency with which a leaf can absorb and use light while performing photosynthesis (Strasser and Tsimilli-Michael 2001). Considered one of the most sensitive of all fluorescence measurements for assessing health, PI has been correlated with early exposure to stress in both forest and agricultural species. (Clark et al. 2000, Appenroth et al. 2001, Hermans et al. 2003). Other indices calculated by the PEA include Fv/Fm, a ratio of the variable fluorescence (Fv) divided by the maximal fluorescence (Fm). FvFm is a useful measure of the maximum quantum efficiency of photosystem II.[1]

Canopy Thinning (Early Stress Response)

After reductions in photosynthetic function, trees typically drop foliage that is no longer providing a net carbohydrate gain (Ayres 1992). This early, visual symptom of decline is often quantified through measurements of foliar transparency or canopy closure. Our preferred method utilizes digital photographs to quantify the percentage of open versus dark pixels averaged across multiple images of the subject canopy (Pontius et al. 2008). This digital method provides a continuous transparency value while minimizing subjective class assignments traditionally used by field crews.

For assessments of individual trees, a digital camera is zoomed in to include only the canopy of the subject tree from multiple locations around the canopy. However, plot level assessments could include full field of view or hemispherical photographs. Digital images are processed as JPG files and quickly processed using freeware such as Gap Light Analyzer .[2] These programs convert color photos to binary light-dark images using an automated transparency threshold (Nobis et al. 2005). The output black-and-white image can be used to calculate a suite of canopy metrics from percent transparency to leaf area index and relative "greenness." Values from a minimum of three photos from the target canopy are averaged to represent overall canopy transparency.

Branch and Limb Dieback (Moderate Stress Response)

As defoliation and transparency increase, clumps of bare branches and limbs become apparent. Some proportion of dieback is natural due to shading and canopy position. Dieback that is related to stress typically begins at the terminal portion of a branch and proceeds toward the trunk (Innes 1998). As a result, stress-related dieback assessments consider only upper and outer branches. Because fine twigs are often lost with wind and the weight of winter snow and ice, fine twig dieback is a measure of recent impacts to health (i.e., dieback within the past year).

Following Forest Inventory and Analysis (FIA) protocol (USDA Forest Service 2004), fine twig dieback is categorized into 5% class intervals by a minimum of two observers. Although it is an ocular estimate, we still encourage its use because dieback is a substantial indicator of stress, widely employed in forest health, with no alternative objective methods. However, researchers can implement several strategies to overcome some of the problems associated with ocular crown measurements, including averaging measurements from multiple field crews (Strand 1996) or remeasurement on a subset of plots by a highly trained team of quality assurance surveyors (Innes 1998).

Live Crown Ratio (Severe Stress Response)

One of the final and most obvious symptoms of decline is a gradual reduction in the size of the photosynthetically active canopy (i.e., shrinking of the live crown). Lower branches are typically lost first in many tree species, progressing up the bole until tufts of live foliage remain at the crown only. Other species, such as sugar maple, may instead lose only one of several main bole stems, making live

Table 1. Mean, standard deviation, and *n* for all species with greater than 100 records in a northeastern forest health database.

	Acer saccharum			*Fagus grandifolia*			*Fraxinus americana*			*Quercus rubra*			*Tsuga canadensis*		
	Mean	Standard deviation	*n*	Mean	Standard deviation	*n*	Mean	Standard deviation	*n*	Mean	Standard deviation	*n*	Mean	Standard deviation	*n*
Crown vigor class				1.60	0.82	130	1.93	1.07	143	1.60	0.71	202	1.42	0.88	382
Defoliation class	0.70	1.02	121	0.29	0.57	144	0.28	0.75	123	0.26	0.61	201			
% Dieback	7.98	8.23	121	8.71	6.76	144	15.18	20.95	163	8.80	9.24	205	12.66	19.62	2,312
FvFm	0.80	0.03	120	0.81	0.03	142	0.80	0.08	147	0.80	0.05	198	0.78	0.06	735
% HWA Infestation													22.24	30.63	1,995
% Live crown	50.09	16.62	121	51.88	15.00	144	46.17	16.28	165	54.21	19.84	204	59.79	20.67	2,140
% New growth													62.29	28.78	2,071
PI	3.35	1.02	120	5.15	3.06	142	3.14	2.01	147	6.68	4.95	198	4.52	4.38	735
% Transparency	12.24	7.99	118	10.01	4.31	143	17.57	9.20	157	16.06	6.76	150	14.82	9.42	2,202

crown ratio less informative of overall condition. This differentiation reiterates the need to assess each measure based on the distribution specific to each species and to consider more than one measure of canopy condition. Following FIA field health assessment protocol (USDA Forest Service 2004), live crown is calculated based on a ratio of the total tree height to the length of the photosynthetically active crown (determined to be the total tree height—the height at the base of the live crown). Live crown is most efficiently and accurately measured using a sonic or laser hypsometer.

Crown Vigor

Crown vigor, such as that used by the North American Maple Project (Cooke et al. 1996), is a common metric of overall condition for hardwoods in the northeast. Canopies are classified into one of five vigor classes by assessing and integrating estimates of defoliation, discoloration, and branch mortality across the entire crown. While this is a very coarse and subjective assessment of canopy condition, it is widely used and provides a metric that attempts to summarize multiple stress symptoms into one summary classification. As such, it can provide a possible quality control check of the more detailed, continuous summary decline rating proposed here.

Species- or Stressor-Specific Symptoms

Depending on the research goals, target species, stress type, stress severity, or equipment available, there may be additional variables of interest that we have not mentioned here. This could include foliar chemistry, epicormic branching (for hardwoods), percent new growth (for conifers), woodpecker activity, or stress-specific measurements such as insect pest densities, leaf scorch, or the density of bole cankers and scars. Time-specific measurements related to vegetation stress could also be included (e.g., the rate or timing of senescence in the fall or spring leaf development). If a variable is related to forest health or tree stress response and can be quantified as a continuous or ordinal variable, it can be included in the assessment presented here. To maximize the information from these variables, we encourage the use of detailed metrics in lieu of broad classes whenever possible. For example, epicormic branching could be quantified into several categories (none, few, many, common) but would be more informative if field metrics could include a count of epicormic shoots or density of shoots per unit length of bole.

Standardizing Field Metrics

To capture the full range of stress symptoms into one variable for a comprehensive analysis, all variables are standardized so that they are weighted to the natural range for each species and standardized to the same scale. We suggest standardization using *z*-scores (Green 1979). *Z*-scores use the mean and standard deviation (SD) of a population to quantify how extreme a given observation is based on a normal distribution (Equation 1).

$$z = \frac{(X - \bar{X})}{s} \qquad (1)$$

Equation 1: *z*-score where $X =$ a single measurement value, $\bar{X} =$ sample mean and $s =$ sample standard deviation.

Using our regional forest health database to randomly select sequentially larger data sets, we conducted a sensitivity analysis determine to the minimum sample size at which mean and SD become stable representations of the larger population. We determined that a minimum of 100 observations, covering the full range of expected values for any given variable is required to accurately represent a species population for *z*-score calculations. Because all studies may not include 100 observations of a given tree species, we provide means and standard deviations for all species with greater than 100 records within our northeastern region forest health database (Table 1).

The *z*-score standardization accomplishes the task of taking measurements of varying scale and converting them to similar units that are biologically meaningful based on the range of values for the target population. For variables like live crown ratio (higher values = healthier trees), *z*-scores are inverted so that higher positive values consistently represent more severe decline symptoms and more negative values consistently represent healthier canopy characteristics.

Sample Calculations

As an example of this process, consider the following six trees randomly selected from our forest health database (Table 2). All six trees include common field measures such as transparency, dieback, and live crown ratio, but each also includes study-specific variables (percentage new growth for *Tsuga canadensis*, epicormic branching for *Fraxinus americana*, and North American Maple Project (NAMP) metrics of crown vigor for *Acer saccharum*).

Using the species-specific average and SD from our forest health database, measured values are converted to *z*-scores, inverted if necessary to associate higher values with more severe decline, and averaged to produce a summary decline rating that represents the overall condition of each tree in one continuous value (Table 2).

One advantage of this approach for ongoing monitoring efforts is that assessments are always made relative to the larger population represented in the *z*-score calculation. In this way, the inherent variability (both geographic and temporal) in tree condition are

Table 2. Sample calculation of the summary decline rating. Six trees randomly selected from the regional forest health database are presented with the field measured value of each variable, *z*-score calculation (based on species average and standard deviation.[3]

Species	Variable	Measured value	Species avg	Species SD	*z*-score	Adjustment	Final variable *z*-score	Tree average *z*-score
TSCA	Dieback	10	12.691	19.745	−0.136	1	−0.136	**-0.574**
TSCA	Infestation	0	21.160	29.569	−0.716	1	−0.716	
TSCA	Live crown	70.6	60.129	20.991	0.499	−1	−0.499	
TSCA	New growth	100	62.265	29.332	1.286	−1	−1.286	
TSCA	Transparency	11.8	13.954	9.184	−0.235	1	−0.235	
TSCA	Crown vigor	2	1.379	0.717	0.866	1	0.866	**0.240**
TSCA	Dieback	5	12.691	19.745	−0.389	1	−0.389	
TSCA	FvFm	0.800	0.773	0.065	0.424	−1	−0.424	
TSCA	Live crown	15	60.129	20.991	−2.150	−1	2.150	
TSCA	PI	3.0	3.289	3.626	−0.080	−1	0.080	
TSCA	Transparency	6.2	13.954	9.184	−0.840	1	−0.840	
ACSA3	Defoliation	2	0.702	1.022	1.270	1	1.270	**0.475**
ACSA3	Dieback	10	7.975	8.230	0.246	1	0.246	
ACSA3	FvFm	0.800	0.805	0.027	−0.175	−1	0.175	
ACSA3	Live crown	55	50.090	16.617	0.295	−1	−0.295	
ACSA3	PI	2.6	3.348	1.016	−0.771	−1	0.771	
ACSA3	Transparency	17.7	12.243	7.993	0.683	1	0.683	
ACSA3	Defoliation	0	0.702	1.022	−0.687	1	−0.687	**0.696**
ACSA3	Dieback	5	7.975	8.230	−0.361	1	−0.361	
ACSA3	FvFm	0.765	0.805	0.027	−1.469	−1	1.469	
ACSA3	Live crown	5	50.090	16.617	−2.713	−1	2.713	
ACSA3	PI	2.1	3.348	1.016	−1.229	−1	1.229	
ACSA3	Transparency	10.7	12.243	7.993	−0.187	1	−0.187	
FRAM2	Crown vigor	2	1.930	1.066	0.066	1	0.066	**0.027**
FRAM2	Defoliation	0	0.276	0.750	−0.369	1	−0.369	
FRAM2	Dieback	10	15.184	20.949	−0.247	1	−0.247	
FRAM2	FvFm	0.784	0.797	0.081	−0.170	−1	0.170	
FRAM2	Live crown	53	46.169	16.280	0.420	−1	−0.420	
FRAM2	PI	1.7	3.135	2.006	−0.702	−1	0.702	
FRAM2	Transparency	20.2	17.571	9.203	0.289	1	0.289	
FRAM2	Crown vigor	1	1.930	1.066	−0.873	1	−0.873	**-0.439**
FRAM2	Defoliation	0	0.276	0.750	−0.369	1	−0.369	
FRAM2	Dieback	5	15.184	20.949	−0.486	1	−0.486	
FRAM2	FvFm	0.797	0.797	0.081	−0.002	−1	0.002	
FRAM2	Live crown	64	46.169	16.280	1.095	−1	−1.095	
FRAM2	PI	2.9	3.135	2.006	−0.106	−1	0.106	
FRAM2	Transparency	14.3	17.571	9.203	−0.359	1	−0.359	

TSCA, *Tsuga canadensis*; ACSA3, *Acer saccharum*; FRAM2, *Fraxinus americana*.

included in the assessment as the population SD. This allows for a more robust assessment of significant change, as well as a comparison to the larger population. If, for example, a tree were calculated to have an average summary *z*-score of 0.43, you could infer based on the normal probability distribution that it has more severe decline symptoms than 66% of all other trees in its population. This provides a particularly useful context when tracking trees over time or over large geographic extents.

Plot- and Watershed-Level Assessments

While the information presented thus far is specific to individual tree canopies, often it is of interest to quantify the condition of a plot or stand of trees. Many ecological studies need to characterize differences or test treatment effects at either the tree, plot, or stand level. To scale up from the tree- to plot-level, we have typically averaged the canopy rating of all measured trees by species and calculated a weighted plot-level average based on a percent basal area (Pontius et al. 2005, 2008).

If the larger plot is the primary sampling unit, it is also possible to include additional plot-level assessments such as percent mortality, canopy gap fraction, leaf area index, and/or hemispherical transparency metrics in addition to, or in lieu of, tree-specific measures described above. In this way, we have used the standardization and averaging approach presented here in geospatial watershed scale assessments, where spatial data layers such as foliar chemistry, forest decline, soil chemistry, and slope were used to create relative indices of watershed sensitivity for each 30 m pixel across the landscape (Hallett et al. 2010).

Summary Decline Rating Validation

To examine how this comprehensive approach compares to traditional metrics and how well it is able to detect subtle differences in forest condition and early decline symptoms, we took a multipronged approach using our regional forest health database of over 3,000 trees: (1) we examined the strength of the correlation between each individual field metric and the resulting summary decline rating to confirm that each individual variable contributes significantly to the summary canopy condition assessment following *z*-score normalization; (2) we plotted the average value of each individual field metric across the full range of summary decline values to identify where each variable contributes the most to canopy condition assessment; (3) we compared the summary decline rating to crown vigor to identify how much information is added by using a continuous condition assessment as opposed to the traditional class rating

Table 3. Nonparametric correlations between input field-measured variables and the final decline summary value.

Variable	Spearman's ρ
Defoliation class	0.6462
Crown vigor class	0.8049
% Dieback	0.8274
FvFm	−0.6277
% Live crown	−0.7775
% New growth	−0.702
Performance Index	−0.5921
% Transparency	0.6839

All are significant at the 0.01 level.

system; and (4) to test the ability of this approach to detect incipient infestation and early decline symptoms, we ran paired *t*-tests on a set of 12 long-term hemlock monitoring plots in the Catskills, NY. These plots were uninfested in year 1, with HWA found on less than 2% of all branches in year 2.

Results and Discussion

A comparison of the summary decline rating described here to each of the originally measured variables for the 3,000 plus subjects in our forest health database shows that the decline rating remains a significant correlate with all of the independent field measures that went into its calculation (Table 3). This significance was expected based on the large sample size and, perhaps more importantly, the circular nature of the *z*-score calculation using each individual metric. However, what this does show is that the summary value retains information relative to each input variable across the full range of possible decline characteristics.

To examine how each individual field metric contributes information to the summary decline rating, we plotted the average value of each variable across the summary decline range from our regional database (Figure 1). Of interest is that the response of each individual metric is not linear or demonstrating a consistent trend across the range of summary decline values. Instead, we see that some variables show a notable change at different ends of the summary decline range. For example, performance index and live crown ratio drop dramatically at the low end of the summary decline range (healthy to early stress response), while other variables such as dieback and canopy transparency remain level (Figure 1). In contrast, variables such as fine twig dieback and canopy transparency seem unresponsive until more severe levels of decline are reached, while performance index and live crown level out. This nonlinear and independent response of each input variable indicates that the summary decline rating is utilizing information from each input variable, with each contributing unique information pertinent at different decline severities. In this way, the summary decline rating is able to differentiate subtle differences in canopy condition that is not possible with any single variable.

For comparison to a more traditional assessment of tree condition, we compared the summary decline rating to crown vigor, a five-class rating designed to capture overall tree condition and incorporate assessments of dieback, defoliation, and missing limbs (Cooke et al. 1996). On the vigor scale, a 1 rating represents a healthy tree and a 2 rating indicates early or mild stress symptoms. Trees classified as vigor 2 for *Tsuga canadensis*, *Fraxinus americana,* or *Acer saccharum* averaged a summary decline value of 0.15, 0.10, and 0.60, respectively (Figure 1). Considering that the summary decline rating is using *z*-score units based on a normal population distribution, this means that vigor 2 is not assigned until a tree is less vigorous than 56, 54, and 73% of all trees in the population (for *Tsuga*, *Fraxinus* and *Acer,* respectively). Thus, limiting analyses to vigor alone would limit the ability to differentiate the condition of over half of all trees in a given population.

To illustrate the importance of this sensitivity to subtle differences in forest condition, we compared yearly changes in the summary decline rating on 12 long-term hemlock monitoring plots with pre- and post-HWA infestation measurements (Table 4). Earlier detection of pests such as HWA is a critical step in developing an eradication strategy for exotic invasive insects. In addition, once populations are established and spreading, earlier detection remains important as we strive to delineate the impacted areas and develop mitigation strategies. However, traditional metrics typically do not identify visual symptoms of decline until many years after the initial infestation (Poland and McCullough 2006). Our comparison of preinfestation and incipient infestation measurements found no significant difference between traditional variables such as percent transparency and live crown ratio ($P = 0.24$ and $P = 0.64$, respectively). There were significant differences in earlier decline symptoms such as reductions in percent new growth ($P = 0.002$) and increases in percent fine twig dieback ($P = 0.001$). However, with a mean change from 4 to 7%, the traditional classification of dieback into five percentage classes would negate the use of this metric for early detection despite its statistical significance. This exemplifies the importance of using metrics that capture earlier symptoms of stress in pest detection efforts. The inclusion of new growth (in conjunction with dieback) is why there was also a significant increase in decline captured in the summary decline rating ($P = 0.005$).

One could argue that because both percent new growth and percent fine twig dieback are significant, these could be used alone to monitor forest health and track extent and spread of forest stressors. However, if early stress symptoms were the sole measure of forest decline, longer term impacts or monitoring of chronic stressors would not be possible. In these severe decline situations, other measures of stress such as crown vigor and live crown ratio better differentiate canopy condition.

The use of one composite index to reflect multiple measurements is not new (Zarnoch et al. 2004, Schomaker et al. 2007). However, the focus of these efforts was primarily on crown geometry. These composite estimates of crown volume, crown surface area, and crown production efficiency were designed to represent a tree's capacity to capture and use solar energy. The intent was to extend the utility of individual crown indicators (Zarnoch et al. 2004). Although similarities exist to the method described here, we have focused on describing a flexible approach to assessing whole tree health, which could incorporate a range of potential input variables depending on the objectives of monitoring efforts and symptoms of specific stress agents.

Tree mortality is the least understood process of a tree's life cycle (Güneralp and Gertner 2007). Manion (1981) proposed a conceptual framework he called the decline spiral model that suggests that there are predisposing factors and inciting or contributing factors in a decline disease cycle. Repeated assessments using the technique described here could help determine where in this conceptual framework an individual tree or a forest lies at any given point in time. In addition, it is possible to determine if health is increasing or decreasing, along with the magnitude of that change.

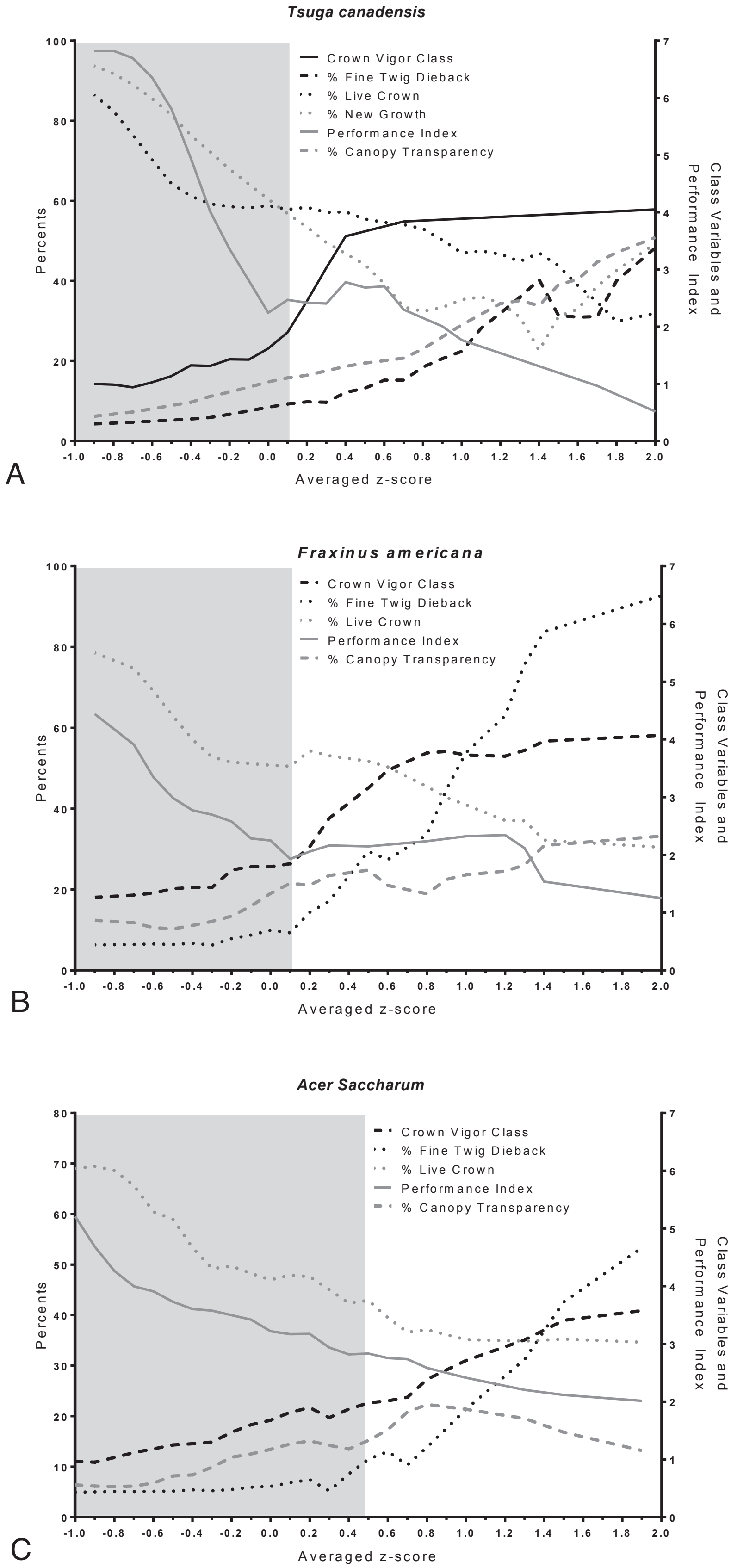

Figure 1. Average field measurements plotted across the calculated summary decline scale provides a glimpse into the nature of the decline symptom progression from initial stress to final mortality. In all three instances (A) *Tsuga canadensis* across the HWA infestation front, (B) *Fraxinus americana* across an EAB front, and (C) *Acer saccharum* across a range of soil cation depletion, all exhibit dramatic decreases PI long before more obvious visual symptoms such as increases in dieback and transparency. This zone of previsual decline (shaded gray where field-measured crown vigor first reaches a value of 2) is captured along with more common measures of decline using the methods proposed here.

Table 4. A comparison of 12 plots monitored the year before and year of incipient HWA infestation shows that measures of early decline (here quantified as percent new growth) are necessary to identify new infestations. While dieback was also statistically significant, its typical assignment into five percent classes would have missed any change between the 2 years.

Variable	Preinfestation	Incipient infestation	*P* value
% Infestation	0	5	
% Dieback	4	7	*0.03*
% Live crown	58	58	
% New growth	82	71	*0.002*
% Transparency	11	12	
z-score	−0.41	−0.24	*0.005*

Conclusions

The methods we have presented are designed to be adaptable to many tree species and stress agents across temporal or spatial measurements. While we suggest some standard metrics to include to capture the full range of vegetation response to stress, these can be modified based on available time, equipment, or objectives. The strength of the proposed approach is not the identification of the one best metric of forest decline but the inclusion of a broad range of decline symptoms within the context of its species' specific characteristics. While some metrics may be insensitive to early decline, others can "fill in the gap." In combination, these metrics allow us to track subtle changes in tree condition that would be missed if only one metric were used.

This fine scale, continuous assessment allows for earlier detection of stress and the detection of subtle changes in condition over time and space. This is of particular importance to forest health monitoring efforts along the front of new invasive pests. In addition, this methodology can track the trajectory of decline (or recovery) once forests have been impacted by a stressor. The techniques presented here can be adapted to other sampling designs, geographic regions, or tree species, producing continuous decline metrics at a variety of scales.

Endnotes

1. For more information on the calculation of various fluorescence parameters, please see www.eko.uj.edu.pl/mycorrhiza/monitoring/hpea.pdf.
2. Please see www.ecostudies.org/gla/ for Gap Light Analyzer or www.cellprofiler.org/ for cell profiler information.
3. Tree species codes match those in the USDA Plants Database (plants.usda.gov).

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