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A Multicriteria Framework for Producing Local, Regional, and National Insect and Disease Risk Maps

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Abstract

The construction of the 2006 National Insect and Disease Risk Map, compiled by the USDA Forest Service, State and Private Forestry Area, Forest Health Protection Unit, resulted in the development of a GIS-based, multicriteria approach for insect and disease risk mapping that can account for regional variations in forest health concerns and threats. This risk mapping framework, used by all nine Forest Service regions and 49 States, provides a consistent, repeatable, transparent process through which interactive spatial and temporal risk assessments can be conducted at various levels to aid in decisionmaking. The national framework was designed to be highly iterative, using input from a wide range of sources including subject area experts. The framework consists of a five-step process: (1) identify agents of concern (insects and diseases) and target-host species; (2) identify, rank, and weight criteria that determine the susceptibility (potential for introduction and establishment) and vulnerability (potential for tree mortality to occur if an agent is established) to each agent; (3) standardize criteria values, and combine the resultant maps using a series of weighted overlays; (4) convert modeled values for each agent to predicted basal area (BA) loss over a 15-year period; and (5) identify regions at risk of encountering a 25-percent or greater loss of total basal area in the next 15 years. This potentially interactive threshold was set by the National Risk Map Oversight team for the national risk map product.

The National Insect and Disease Risk Map resulted in the integration into a national map of 186 forest insect and disease models, individually run and assembled on a central server located at the Forest Health Technology Enterprise Team (FHTET) in Fort Collins, Colorado. The national framework also enables local knowledge and data to be entered into models, allowing for quick, large-scale assessments. The development of this national framework is described here.

Keywords: Forest health monitoring, GIS, insect and disease risk, multicriteria modeling, NIDRM, risk map.

Introduction

Ensuring the health of America's forests requires the analysis, understanding, and management of complex and interrelated natural resources. Increasing human-use pressures, a continual threat from native and exotic insects and diseases (USDA FS 2005), and more complex management policies make natural resource management demanding. To accurately assess where and how forest resources are being impacted, resource managers and policymakers require information beyond tabular summaries. In turn, this requirement has created an increasing need for spatial-based, decision-support systems that can quickly summarize a wide range of tabular and geographic information. Such systems provide resource managers with the information they need to make clear, informed choices and efficiently allocate human and financial resources. Therefore, integrated and comprehensive approaches that use technologies, such as geographic information systems (GIS), with their ability to analyze a large number of spatial variables concurrently, are becoming increasingly important for the protection and management of our Nation's forest resources (Ciesla 2000, McRoberts and others 2006, Mowrer 1992, Reynolds 1999, Stein and others 2005).

The primary goal in the development of the 2006 National Insect and Disease Risk Map (NIDRM) is the creation of a national communications tool that will provide policymakers, USDA officials, and Federal and State land managers with a periodic, strategic assessment for risk of tree mortality from major insects and diseases. NIDRM is an integration of 186 individual risk models constructed within a common, consistent, GIS-based, multicriteria framework that accommodates regional variations in current and future forest health conditions, knowledge, and data availability. The 2006 NIDRM was created through a modeling process that is repeatable and transparent, and through which interactive spatial and temporal risk assessments can be conducted at various scales to aid in the allocation of resources for forest health management. This process is intended to increase the utilization of forest health risk maps within and outside the National Forest System.

The production of the 2006 risk map has been a highly collaborative process, coordinated by the USDA Forest Service, State and Private Forestry Area, Forest Health Monitoring Program (FHM). Entomologists and pathologists from all States and every FHM region were invited to take part in the process of developing the NIDRM. Teams were created with forest health and GIS specialists from the Forest Service, State agencies, and academia to oversee and assist in model development. Even though the goal of the authors is to describe in this paper the GIS framework developed for the construction of NIDRM and to briefly demonstrate how this process can be used to conduct assessments at multiple spatial scales, the authors want to emphasize the importance of a team approach that ensures participation from local resource managers.

The Assessment Framework

Defining Risk

The definitions for "risk" and "hazard" in forest pest management can be confusing and contradictory. Rather than reconcile the various definitions of risk and hazard we use the following construct.

When assessing risk as it relates to forest health, risk is often composed of two parts: the probability of a forest being attacked (susceptibility) and the probability of resulting tree mortality (vulnerability) (Mott 1963). Characterizing the spatially explicit probability of insect and disease activity requires spatially explicit quantitative data. However, because such data are often lacking at regional, national, and local levels, we define risk as the potential for harm owing to exposure to an agent(s). Also, we draw the distinction between susceptibility and vulnerability (Mott 1963), but in the context of potential rather than probability.

Our threshold value for mapping risk is defined as the expectation that, without remediation, over the next 15 years 25 percent or more of standing live basal area (BA) in trees greater than 1 inch in diameter will die owing to insects and diseases. The threshold value for mapping insect and disease risk is independent of the GIS framework discussed in the remainder of this paper. Therefore, the framework can support any threshold.

A Conceptual Overview of a National Risk Assessment Framework

Figure 1 provides a conceptual overview of the risk-assessment process discussed here. The modeler first indicates whether the forest pest under study is endemic or not. If a pest is established throughout a region, then the potential or source for actualized harm is assumed to be equal everywhere, and all host material is susceptible. In such cases, susceptibility assessments are not required. If a mechanism or data set exists that addresses varying pest densities in time and space, we can accommodate those densities within our framework. However, few national data sets for pest density exist, and we assume presence or absence in our modeling scenarios. A vulnerability model, which determines the likelihood and extent to which trees will be harmed by the pest of concern within the defined time frame of 15 years, is required to complete a risk assessment in a case where a pest is already established.

When considering forest pests, either nonnative exotics that have not been established or cyclic native pests whose outbreaks occur sporadically about the landscape, the modeler must first construct a model of pest potential or susceptibility. Susceptibility is based on the biological availability of a host and the potential for introduction and establishment of a forest pest within a predefined time frame (in this case, 15 years). With a susceptibility model constructed, the next step is to determine whether a forest pest will always kill its host.

Generally, once established, some risk agents, such as sudden oak death (*Phytophthora ramorum*) and chestnut blight (*Cryphonectria parasitica*), harm their hosts in the same manner throughout the landscape, regardless of existing site and stand conditions. This applies to exotics and

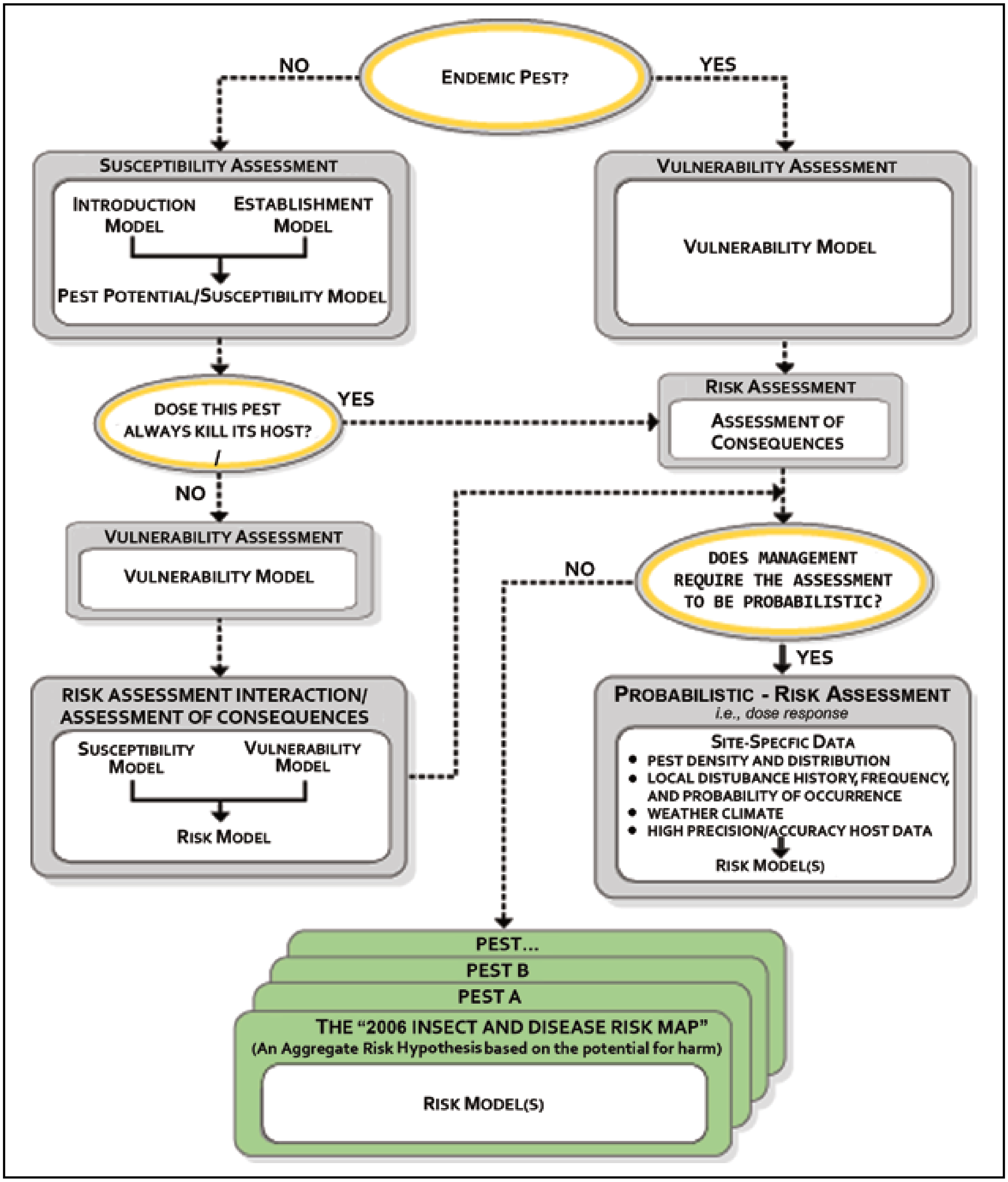


Figure 1—Risk assessment framework provides a conceptual overview of the multicriteria risk assessment framework used to construct the 2006 National Insect and Disease Risk Map (NIDRM).

native species, alike, although some exotic pests, such as gypsy moth (*Lymantria dispar*), produce mortality rates that can differ greatly depending on site and stand conditions. If a vulnerability assessment is not required, i.e., pest effects are not site-dependent, then the susceptibility model can be used for the final risk assessment.

In some cases, as in the case of gypsy moth where both susceptibility and vulnerability models are run, the interaction of these models creates the risk assessment. The degree to which either vulnerability or susceptibility always results in harm determines how much influence each model has on the final outcome of the risk assessment. Think of the interaction between susceptibility and vulnerability as being on a continuum, whereupon agents such as gypsy moth are at or near the middle where both susceptibility and vulnerability receive equal influence, and risk agents such as sudden oak death and mountain pine beetle (*Dendroctonus ponderosae*) require only vulnerability assessments. All forest pests fall somewhere on this continuum. When a risk assessment is in hand, estimates of potential BA loss over the next 15 years can be derived.

A GIS-Based Multicriteria National Risk Assessment Framework: A Five-Step Process

The risk assessment framework used to construct NIDRM is best explained using a hypothetical example, particularly in steps 2 through 5. (A real world example is not used here, so the reader is free to focus on the process rather than the correctness of the example.) It should be noted that the modeling process presented is not limited to regional or national-level work; rather, it is designed to be usable at any scale. This is illustrated in the latter part of this paper. However, the accuracy of the model outputs depends on knowledge about forest pest behavior, the degree of informed personal judgment of the model developers, and the spatial accuracy and precision of the data driving the models.

Because of its availability from State and Federal agencies, ease of use, and relative stability, ESRI ArcView 3.x Spatial Analyst 2.x ModelBuilder was selected as the software for the multicriteria framework. In addition, previous familiarity with ESRI Spatial Analyst 2.x among GIS specialists greatly reduced the rollout time of the risk assessment framework. Other commercial software that supports multicriteria modeling includes IDRISI and ESRI ArcGIS 9.x ModelBuilder. IDRISI (Eastman 2001, Eastman and others 1995) has a very comprehensive set of multicriteria modeling tools, but is not widely used in the Forest Service. In addition, the Ecosystem Management Decision Support (EMDS) (Reynolds 1999), an ESRI ArcGIS extension at version 3.0, was developed within the Forest Service to support local and regional decisionmaking and to provide a framework for conducting knowledge-based ecological assessments.

Step 1: Identify Risk Agents and Host Species— Often, forest pest distributions are limited to specific climatic or biophysical regimes or both. In addition, pest behavior and population dynamics often differ by geographic area and must be modeled differently to accommodate local and regional conditions. It is possible within the NIDRIM framework to account for this variation by constructing multiple models for an individual forest pest. In order to better capture this natural variation and to prevent models from differing along political boundaries, models were constrained to the extents of Bailey's (2004) ecoregions. Because ecoregions capture broad climatic and biophysical patterns, they provide a more realistic base map on which to delineate differences in forest-pest models.

For much of the remaining discussion, we will use the following hypothetical example: risk agent X is a nonendemic pest that attacks aspen in the central Rocky Mountains. The amount of aspen mortality occurring in infested trees varies according to site conditions. Because of this, risk assessments for agent X require the construction of both a susceptibility and vulnerability model (Figure 1).

Step 2: Identify, Rank, and Weight Criteria— After risk agents and host species are identified, the criteria (factors and constraints) that determine both the potential for risk-agent establishment and host vulnerability for potential mortality must be identified. For the risk assessment framework presented here, we define:

- **Susceptibility** as the potential (rather than probability) for introduction and establishment, over a 15-year period, of a forest pest within the range of a tree species.
- **Vulnerability** as the potential (rather than probability) for mortality of a tree species at a maximum realizable mortality rate over a 15-year period if a forest pest were to become established.

Table 1—Sample weights for vulnerability to risk agent X

Criteria	Weight
BA	65 percent
QMD	22 percent
Soil Dry/Wet	13 percent

Weights always sum to 100 percent and represent the relative importance of each criterion.

Regions that are both very susceptible to a pest attack and highly vulnerable to its effects (as where many trees that are weakened or stressed are present) are the most likely to experience the maximum realizable mortality rate—an estimation of the largest likely mortality loss for a risk agent over a 15-year period. Regardless of how vulnerable trees are at any given location, they will not experience mortality from a risk agent if these regions are not susceptible to attack. In other words, under some circumstances, susceptibility can act as a constraint. Constraints are criteria that must be met for susceptibility and vulnerability potential to occur at any given location. For our hypothetical risk agent X, we have assigned the maximum realizable mortality rate of 100 percent, meaning that risk agent X is always lethal to aspen when all criteria for susceptibility and vulnerability are met. With risk agent X isolated, we can now identify a set of criteria for susceptibility and vulnerability.

Factors for susceptibility are:

1. Distance to known infestations
2. Average annual minimum extreme temperature
3. Aspen host presence, with the latter criterion acting as a constraint.

Factors for vulnerability are:

1. Aspen BA
2. Aspen quadratic mean diameter (QMD)
3. Soil dryness/wetness

Although risk agent X requires both a susceptibility and vulnerability model for its risk assessment, recall that risk assessments for some pests require only one or the other.

Many forest pests invariably cause tree mortality whereas others only contribute to their demise. Stressors often work in concert to cause mortality. Modeling pest complexes that may work together to cause mortality requires a layer (or layers) representing the distribution and intensity of each insect and disease that contributes to the mortality in any given area. Depending on whether the additional agent(s) contributes to an increased risk of establishment or mortality or both, this layer is then used as a criterion in the susceptibility or vulnerability models of the primary risk agent. Owing to the lack of understanding of the interactive effects among multiple stressors, we treat interactions as additive. The exception to this is where we use one pest risk model to constrain the other. If the interactive effects of risk agents are understood, we can model them under this current framework.

The relative importance of each criterion, or rank, for determining whether an area, or pixel, has the potential to be susceptible and vulnerable to a risk agent is entered into a pairwise comparison matrix. A pairwise comparison matrix is a robust method for assessing the comparative importance of factors (Eastman 2001, Eastman and others 1995, Saaty 1977). It is particularly useful when attempting to derive weight evaluations for multiple criteria under many considerations. Every possible pairing of factors must be identified and entered into the matrix, ordering the criteria most important to least important. The matrix is used to generate a set of weights representing the relative importance of each criterion (Table 1). The resultant weights, expressed as percentage influence, must sum to 1 (or 100 percent) and are used to combine criteria values within a weighted overlay (see step 3). Separate matrices are generated for both susceptibility and vulnerability. A matrix is not needed if only a single criterion is present.

Prior to entering values into the pairwise matrix, comparisons must be made between criteria using a 10-point continuous rating scale (Table 2) modified by Krist (2001, 2006) from the 9-point scale Eastman uses in the IDRISI software (Eastman 2001, Eastman and others 1995). Rankings in Table 2 represent the relative importance of each criterion. For example, QMD is moderately less important than BA for determining the vulnerability potential to risk agent X; therefore, QMD receives a value of one-third in the comparison matrix whereas BA receives a value of 1. Soil

Risk Model Worksheet - Interior West

Risk Agent(s):	Risk Agent X	Host(s):	Aspen
Model Extent:	Central Rocky Mountains	Max Percent Mortality:	100%

Susceptibility

Rank/Weight 1 50%	Criterion	Risk Begins (a)	Risk Peaks (b)	Risk Decreases (c)	Risk Ends (d)	Curve	Rank	Weight
Criteria 1	Dist. To Known Infestations (km)	0	0	0	200	Linear	1	75%
Criteria 2	Avg. Minimum Extreme Temperature (F)	-20	0	0	0	Linear	1/3	25%
Criteria 3								
Criteria 4								
Criteria 5								
Criteria 6								
Criteria 7								
Criteria 8								
Criteria 9								
Criteria 10								

Vulnerability

Rank/Weight 1 50%	Criterion	Risk Begins (a)	Risk Peaks (b)	Risk Decreases (c)	Risk Ends (d)	Curve	Rank	Weight
Criteria 1	Aspen BA (sq. ft./acre)	20	120	120	120	Linear	1	65%
Criteria 2	Aspen QMD (in.)	0	10	10	10	Linear	1/3	22%
Criteria 3	Soil Dryness/Wetness	20	20	20	50	Linear	1/5	13%
Criteria 4								
Criteria 5								
Criteria 6								
Criteria 7								
Criteria 8								
Criteria 9								
Criteria 10								

Constraints	Aspen host must be present.	Comments	
Citations	2, 8, 15	Model Certainty	4 - Expert Opinion

Figure 2—The spreadsheet template allows staff to document models, rank criteria, and calculate weights. Values shown are for the risk agent X example.

Table 2—10-point continuous rating scale

Description	Comparison rating
Most important	1
	1/2
Moderately less	1/3
	1/4
Strongly less	1/5
	1/6
Very strongly less	1/7
	1/8
Extremely less	1/9
	1/10
Unsuitable	N/A

dryness/wetness is of strongly less importance to BA and is assigned a value of one-fifth.

The 10-point rating system enables forest health specialists to select the most important factor(s) and compare the remaining criteria to it (them). All these criteria have a positive influence and contribute to potential. The negative impacts of a criterion can be accounted for by reversing the rankings for the criterion values, thus turning a negative relationship into a positive one (one that contributes to potential).

We simplified the workload of regional forest health specialists constructing models by enabling the spreadsheet (Figure 2) used to collect model information to simulate the comparison matrix developed by Saaty (1977) and to calculate weights automatically. Having the ability to calculate weights automatically enables the user to see changes in weights immediately as ranks are adjusted. The weights in the spreadsheet are calculated by first summing all the rank values and then dividing each rank by that sum.

In addition to weighting risk agent criteria, weights must be assigned to susceptibility and vulnerability, based on their importance in determining the potential for a tree species to experience the maximum realizable mortality rate from the pest of concern in the next 15 years. These weights are used to combine the resultant susceptibility and vulnerability models in the final risk assessment (see step 3). In the case of risk agent X, equal weight (50 percent) was given to both susceptibility and vulnerability. Remember that susceptibility acts as a constraint in the final risk assessment; areas with no possibility of being susceptible in the next 15 years are not at risk.

Criteria, rankings, and weights for risk agent models can be selected in a number of ways. Ideally, if data on the distribution and intensity of a risk agent exist, statistical analyses may be performed in the hopes of identifying relationships between risk agent activity and forest and biophysical attributes, as represented in GIS layers. If such a relationship is found, the strength of the correlation can be used to determine weights. Unfortunately, this data-driven or literature/research-based approach is not always possible because, in many instances, data on risk agent distributions, intensity, and behavior are either inadequate or incomplete or both. In such instances, modelers must rely on informed professional judgment or expert opinion or both when selecting criteria and weights.

The information collected for steps 1 and 2, including the basis for a model or model certainty, appears in Figure 2.

Step 3: Standardize Criteria Values and Combine the Resultant Maps—

With the risk agent criteria and their corresponding GIS layers identified and weights generated for susceptibility and vulnerability, the factor values must be standardized, based on a common evaluation scale. Standardization allows for the comparison of criteria with differing values, such as BA, with units of square feet per acre and QMD, with units in inches. An evaluation scale from 0 to 10, with 0 representing little or no potential, and 10 representing the highest potential, was chosen. For example, in the case of risk agent X, higher stocked stands are more vulnerable; therefore, areas with stocking levels approaching 120 square feet or more are given a value of 10 (Table 3). Potential in areas with less than 20 square feet of aspen is very low and is assigned a 0. Assigning a 0 to a criterion does not eliminate the possibility for risk to occur. If other criteria have values greater than 0, potential is still possible at a location.

Table 3—Rankings for BA (basal area) using linear and sigmoidal memberships

BA	Rank (linear)	Rank (sigmoidal)
ft^2/ac		
20-30	0	0
30-40	1	0
40-50	2	0.3
50-60	3	1.2
60-70	4	2.5
70-80	5	4.1
80-90	6	5.9
90-100	7	7.5
100-110	8	8.8
110-120	9	9.7
>120	10	10

Fuzzy memberships enable values to be reclassed or recoded in a variety of ways to capture relationships between insect and disease behavior and criteria. This example demonstrates the effects of two commonly used memberships on BA, with 10 representing the highest potential for risk.

Regions without aspen are constrained. Constraints do not need to be standardized, but they do restrict modeled potential to specific areas, such as regions containing aspen or areas within a certain distance of current risk agent infestations. Because of the restrictions, the potential for risk can be precluded in some areas, regardless of the strength of the other criteria.

For simplicity, and due to the frequent lack of precise data layers or models or both at the national level, an integer scale from 0 to 10 was chosen. At a finer resolution and with more precise data, an extended standard scale may be of more use (e.g., an integer scale of 0 to 100 would capture a wider range of variation in the data).

A standard scale may be applied to a GIS data set through a manual recoding of the criterion values. This is particularly easy to do when data have sharp boundaries and discrete classes. However, this is not an easy task when the transition from criterion values with potential to values without potential is gradual. Consider the BA criterion in our example. Potential for vulnerability to pest X ends or

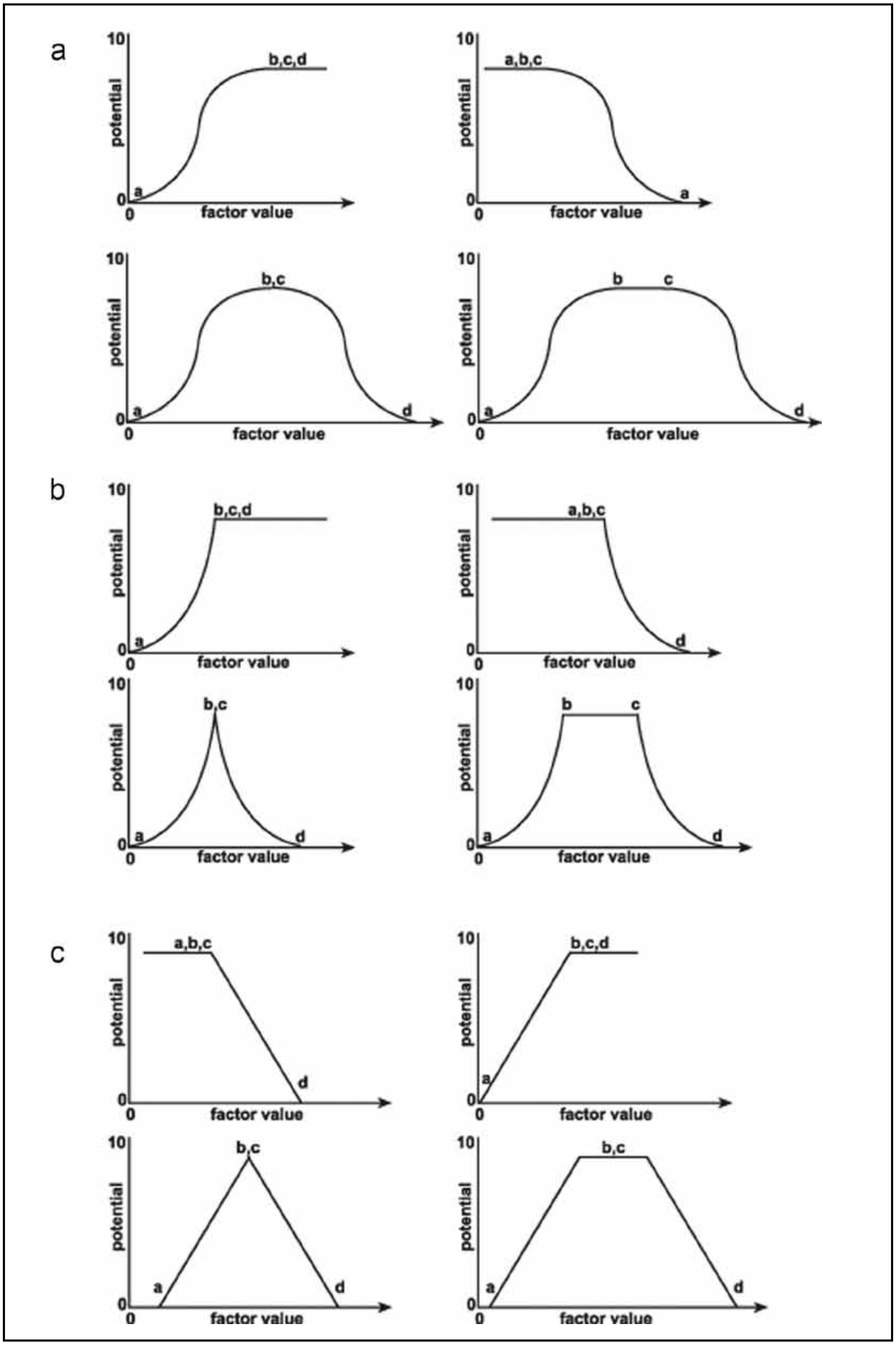


Figure 3—Available fuzzy memberships include: (a) sigmoidal functions, (b) J-functions, and (c) linear functions. Custom functions can be developed, based on the relationship of the data to potential risk.

is very low when stocking levels are at or below 20 square feet and increases gradually until stocking levels reach 120 square feet. Rather than manually break down this range into 10 discrete classes, a fuzzy membership set (Eastman 2001, Eastman and others 1995) can be used to stretch or assign a continuous set of values, automatically. Another advantage to selecting a fuzzy membership is that the data can be assigned standardized values in differing ways, depending on how potential varies within a criterion. The most common method of assigning values based on fuzzy membership is a simple linear stretch in which potential increases linearly. However, if potential rises gradually and then accelerates and tapers off, a sigmoidal function may capture the natural variation more precisely.

Twelve fuzzy membership functions were used in the construction of NIDRM models, including linear, sigmoidal, and J-shaped functions (Figure 3). Table 3 shows the difference between the resultant values of a linear and sigmoidal stretch, the most common memberships used during the production of NIDRM. The letters (inflection points) on the graphs in Figure 3 represent where risk potential (**a**) begins, (**b**) peaks or reaches its highest, (**c**) begins to decrease (though this may or may not happen), and (**d**) ends or no longer changes (levels off). In the risk agent X example, **a** is set to 20 square feet of BA whereas **b**, **c**, and **d** are set to 120 square feet. Notice the letters and descriptions on the column headers of the spreadsheet in Figure 2 and the Curve column, where a fuzzy membership (curve) is chosen for each criterion.

ESRI ArcView 3.x Spatial Analyst 2.x ModelBuilder does not contain a routine that will automatically recode or stretch criterion values according to a fuzzy membership, so a worksheet was developed to calculate break points that could then be manually entered into the RECLASS module of ESRI ModelBuilder (Figure 4), effectively dividing the values into 11 classes. Values for each risk agent's criteria were manipulated in Model Builder in this way. Figure 5 illustrates what a set of standardized GIS layers would look like for the central Rocky Mountains using risk agent X as an example.

With weights generated and values standardized for each criterion, all criteria can be combined in a series of weighted overlays representing susceptibility, vulnerability, and the final risk-agent-mortality assessment. Factors are combined within a weighted overlay or weighted linear combination by multiplying the factor weight by each criterion value, followed by a summation of the results (Saatty 1977):

$$\mathbf{P} = \sum w_i x_i$$

where:
P = potential for susceptibility, vulnerability, and risk
W_i = weight criterion i
X_i = criterion score of factor i

Figure 6 illustrates how sample values from risk agent X are combined in a series of three weighted overlays. The output from each weighted overlay has a value from 0 to 10, the same as the standard evaluation scale used for each criterion (Figure 5). The higher the value, the greater the likelihood or potential for a tree species to be susceptible or vulnerable to a risk agent. The greater the value from the weighted overlay of the resultant susceptibility and vulnerability maps, the greater the likelihood or potential for a tree species to experience mortality over the next 15 years.

ESRI ModelBuilder provides a weighted overlay module in which criteria can be entered, weighted, and formally ranked. Figure 7 shows the Model Builder weighted overlay for the risk agent X vulnerability model.

Step 4: Convert Modeled Values to an Estimate of BA Loss—

Using a standardized scale from 0 to 10 allows for the easy conversion of risk potential to estimates of BA loss. Recall that when all criteria are met for susceptibility and vulnerability within a particular area or pixel, the host species within that area is likely to experience the maximum realizable mortality rate over the next 15 years. Based on this assumption, a pixel in our agent X risk assessment receiving a value of 10 would be assigned a 100-percent mortality rate, whereas a pixel with a value of 5 would receive a 50-percent mortality rate. Once pixels have been assigned their mortality percentages based on their mortality potential, this layer is multiplied by a surface representing host BA to produce loss estimates for a tree species. For example, a stand with 100 BA of aspen and a simulated

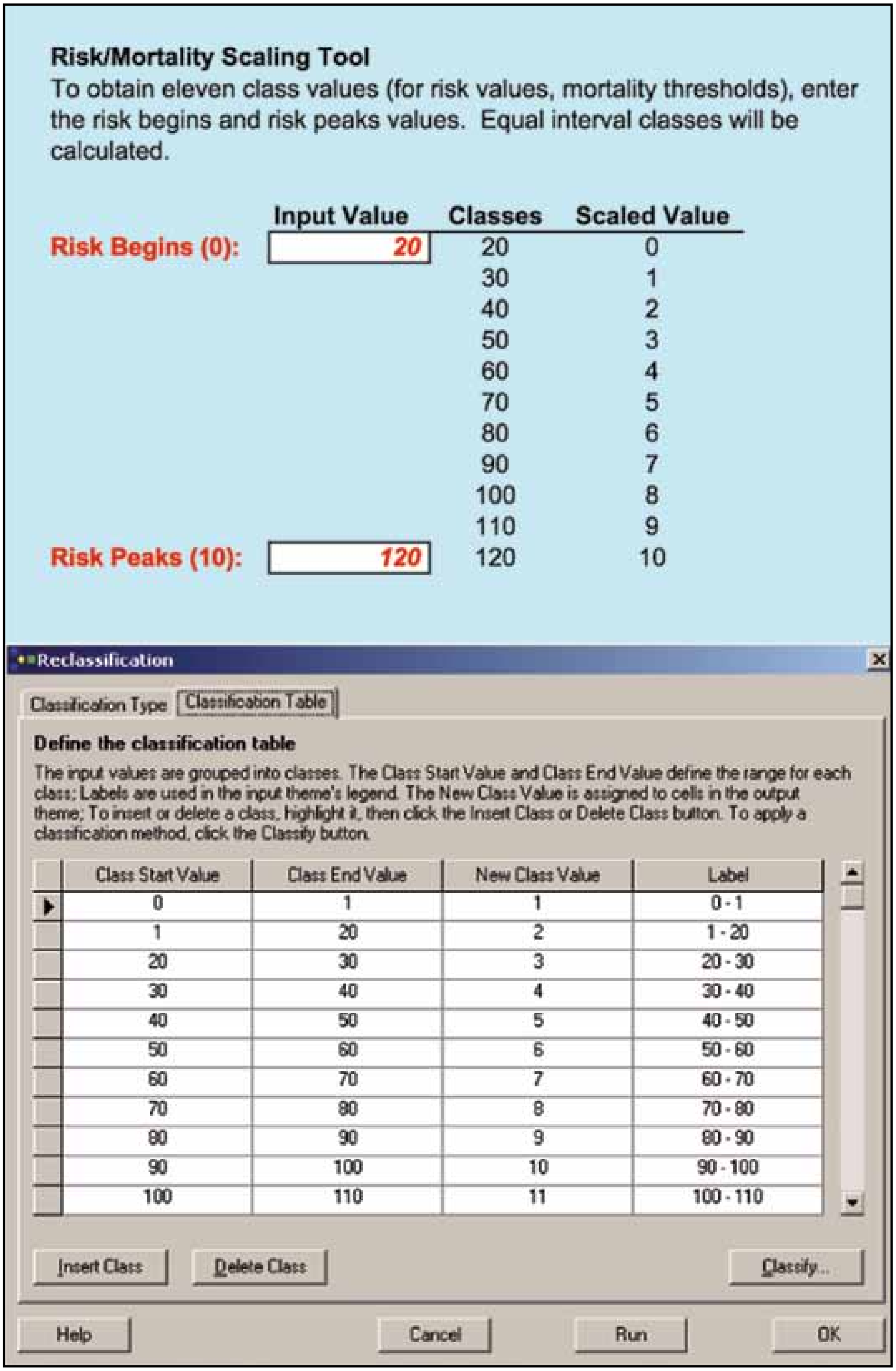


Figure 4—Criteria-ranking tool and RECLASSIFICTION module in ModelBuilder are shown. The criteria-ranking tool divides factor values into classes that can be entered into ModelBuilder using the RECLASSIFICTION module.

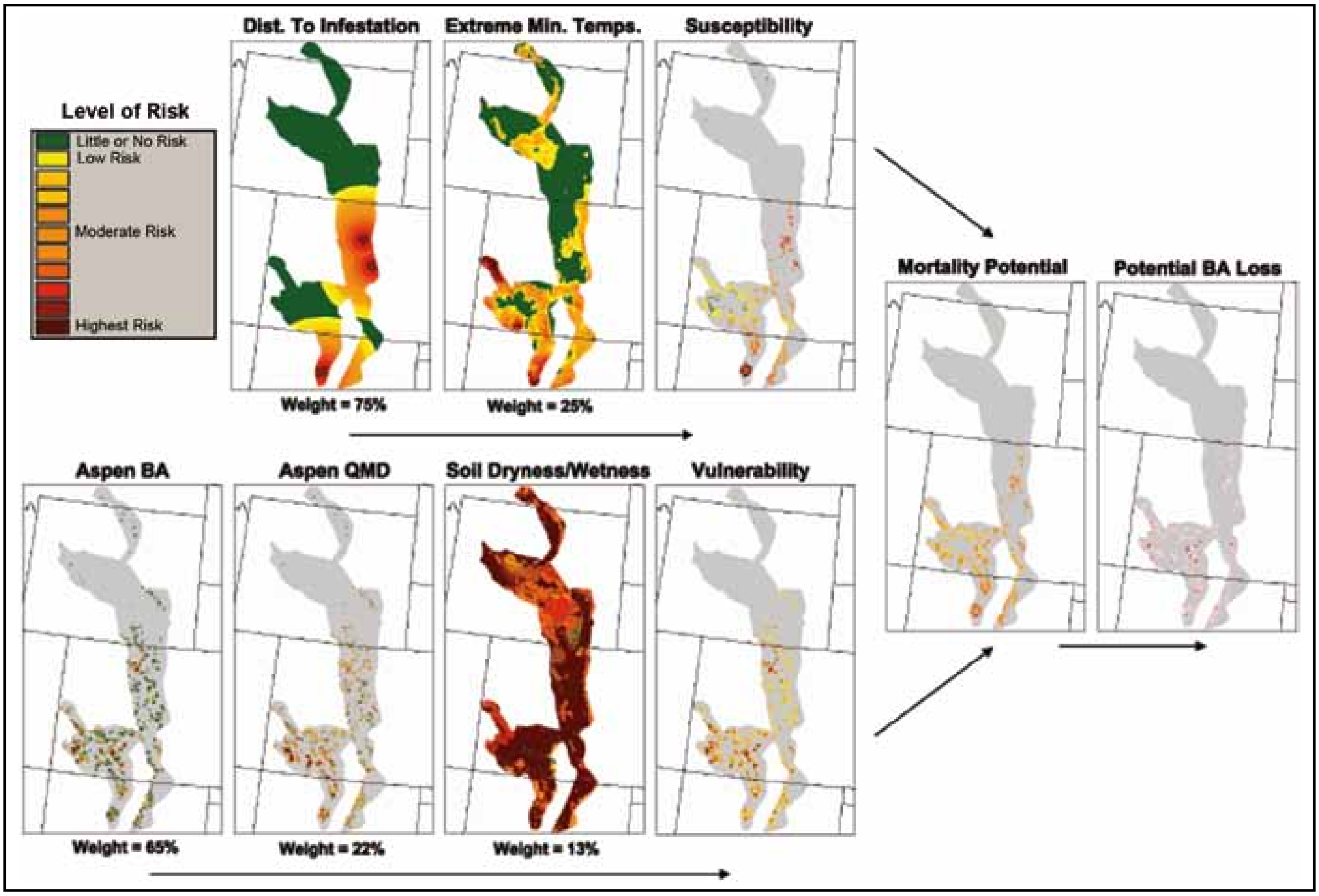


Figure 5—Sample criteria maps and resultant model outputs are shown below. All criteria used in the risk agent X model are displayed with their corresponding weights. Notice how each layer affects the outcome. Arrows show the direction of flow during model construction.

mortality potential for risk agent X of 5 could lose 50 square feet of basal area (50 percent × 100 BA) in the next 15 years. Remember, model results do not guarantee that mortality will occur at any given location; rather they suggest the **potential** for loss. Figure 5 shows the map of BA loss for Risk agent X.

In cases where multiple pests are acting on a single forest species, the resultant BA losses cannot be added up to calculate total BA losses. For example, if one agent attacks a resource and has the potential to kill 75 percent of the trees and another agent attacks the same resource in the same area and may kill 75 percent of the trees, it is incorrect to say that up to 150 percent of the trees may be killed. Under the simplifying assumption that mortality agents act independently (a common assumption in the development of the NIDRM), mortality from multiple agents is calculated as:

$$D = 1 – (1\text{-}p1)(1\text{-}p2)(1\text{-}p3)...\ (1\text{-}pn)$$

where:

D = total proportionate mortality

p1 = proportionate mortality caused by agent 1

n = n^{th} agent

In the example above where two agents may each cause 75-percent mortality, 94 percent of the total BA would be lost in that pixel when total losses are calculated using the simplifying assumption:

$D = 1 – (1\text{-}\ p1)(1\text{-}\ p2)$

$D = 1 – (1\text{-}\ 0.75)(1\text{-}\ 0.75)$

D = 0.9375 or 94 percent

We realize this mechanism does not address complex interactions between various pests. The body of literature

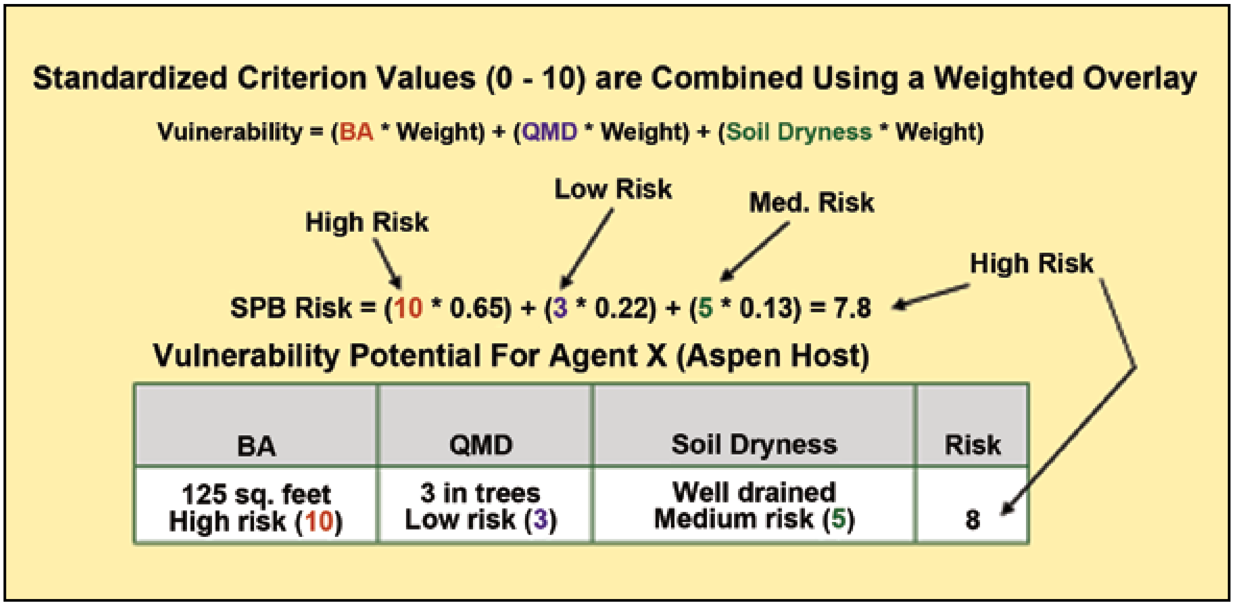


Figure 6—Weighted overlay for the risk agent X vulnerability model is displayed. Notice how much influence the relatively high weight for BA has on the final model outcome.

regarding pest interactions is limited, and cumulative impacts are not understood well enough so that complex interactions can be modeled with confidence.

Step 5: Identify Regions at Risk—

To calculate the percentage of total BA that might be lost in each pixel, estimates of potential 15-year BA loss compiled for all risk agents in step 4 were divided by a surface representing total BA. Pixels where the total loss exceeded or met 25 percent of the total BA were flagged for the national composite risk map (NIDRM). Because the original percentages are available, different threshold values for risk can be defined and mapped. Risk owing to individual pest species by host also were provided.

Modeling at Multiple Scales/Resolutions

Once a model has been constructed in ESRI ArcView 3.x Spatial Analyst 2.x ModelBuilder, models can be rerun at multiple scales. The GIS layers can be swapped in and out of ModelBuilder with little or no modification when standard measurement units exist across scales. As additional data become available at finer scales, supplementary criteria can be added to the model. Figure 8 shows the same southern pine beetle (*Dendroctonus frontalis*) (Thatcher and Barry 1982) model run at three different resolutions (1 km, 250 m, and 30 m). The 30-m-resolution model includes an additional criterion depicting forest stand connectivity.

Discussion/Conclusions

The 2006 national risk assessment employed 186 risk-agent models representing over 50 risk agents acting on 61 tree species or species groups, with all models assembled into a national composite (NIDRM) (Figure 9). Given the nature of our assignment to construct a national, 15-year assessment of forest health risk from insects and diseases, we believe that NIDRM is successful because it is:

1. Based on an integrating technology. NIDRM represents the collection and integration of multiple risk models developed through an iterative, hands-on process by local forest health specialists. The risk assessment frame-work presented in this paper is able to integrate outputs from a wide range of models and is implemented through software that gives forest health specialists direct access to GIS models.
2. Transparent and repeatable. The 2006 modeling framework provides a consistent, repeatable, transparent process to conduct risk assessments.

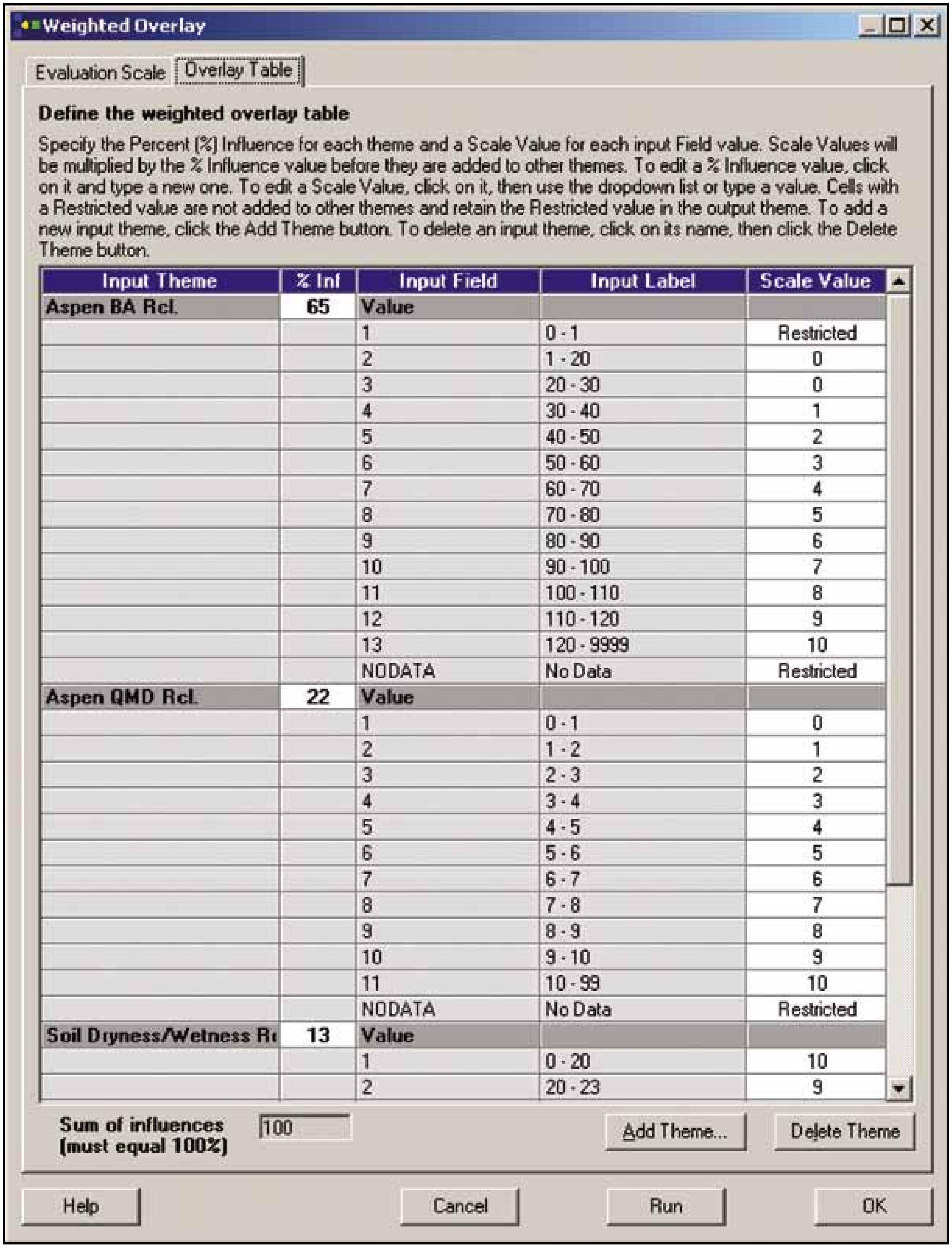
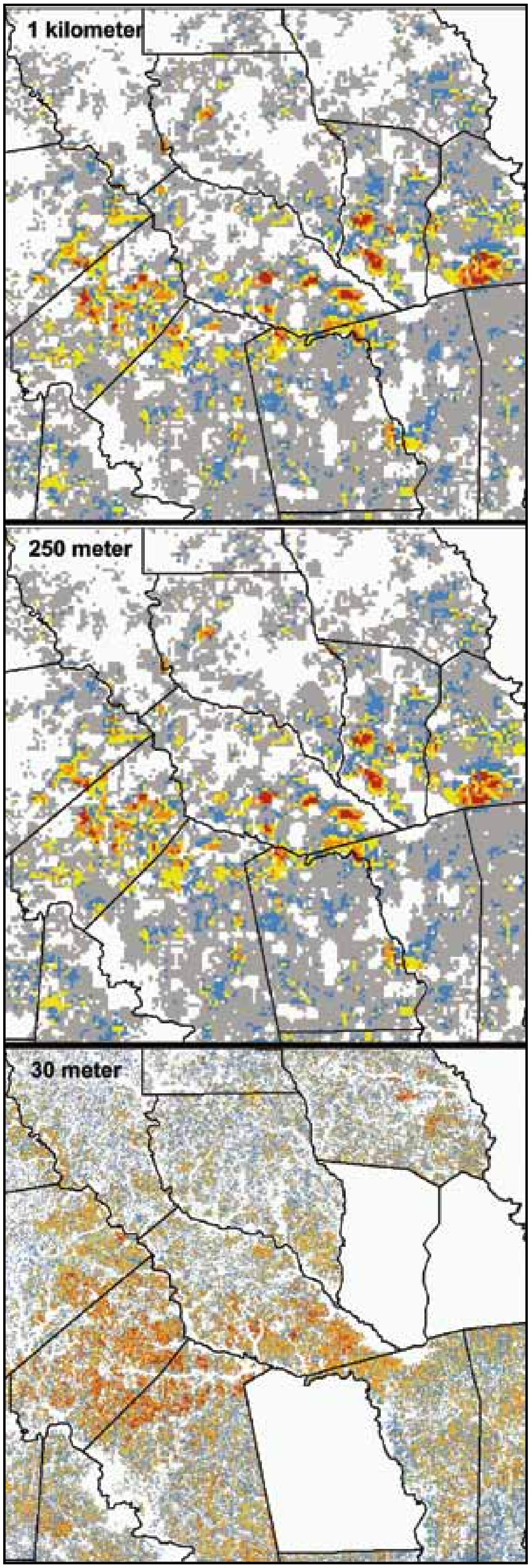


Figure 7—The ModelBuilder weighted overlay module provides a user friendly interface in which criteria can be combined in a multicriteria model. This module also provides a means of documenting model information and can be used to rerun a model using various weights and ranks.



Within this framework, forest health specialists are able to determine why an area is at risk, what the source data are, and how the model(s) for that region were constructed, thus documenting any models composing NIDRM. This type of framework also enables shortcomings in data and models to be identified and can be used to prioritize future research and data development.

3. Interactive and scalable. The framework is interactive enough to support sensitivity analysis while allowing risk assessments to be conducted at various spatial and temporal scales. Sensitivity analysis ensures that models can be adjusted according to local knowledge or as additional data and models become available or both. Scalability enables subject area experts to conduct local and regional assessments using an identical framework. This continuity ensures that national products do not conflict with local knowledge.
4. Efficacious. Efficiency, precision, accuracy, and usability must be considered when developing a framework. A national risk-map product with potentially hundreds of models behind it not only requires a highly efficient modeling process, it must be able to capture the information and variation within each individual model. With a wide range of audiences, including both subject area experts and private citizens, the risk map framework is able to produce detailed model documentation and results that are easy to interpret.
5. Comparable across geographic regions. The 2006 modeling framework has resulted in a standard modeling process that provides a level playing field for every region being examined as part of NIDRM. This ensures that regional comparisons can be made. Without standardization, NIDRM would be little more than a federation of maps with little or

Figure 8—Southern pine beetle risk models are shown in the following: each map depicts the potential for southern pine beetle mortality in a portion of east Texas. Red represents extreme risk, orange, high, yellow, medium, and blue, low.

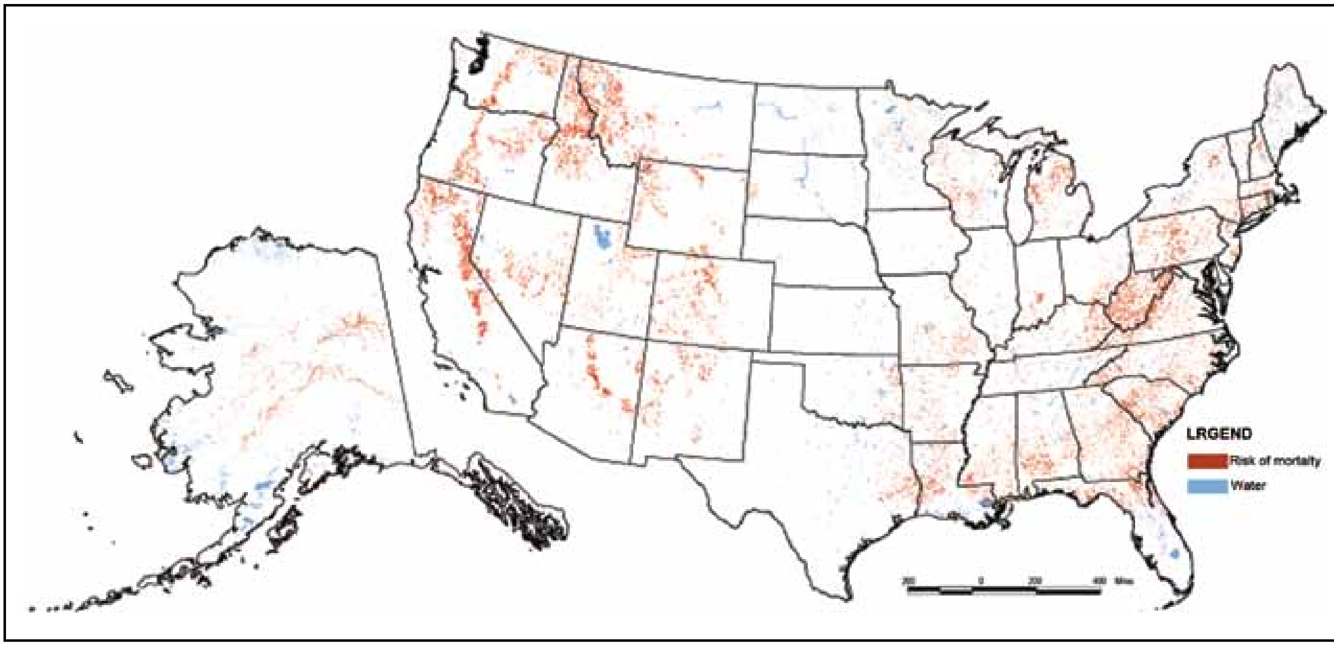


Figure 9—2006 National Insect and Disease Risk Map (NIDRM) for the United States characterizes the potential for significant losses (at or above 25 percent) of total forest basal area (BA), spatially.

no consistency between them, making regional comparisons and national summaries impossible.

Although the framework described in this paper was developed around modeling potential risk of tree mortality from insects and diseases, the process can be used for a wide range of other applications including estimating potential for wildlife and forest habitat (Krist 2001, 2005).

Literature Cited

Bailey, R.G. 2004. Bailey's ecoregions and subregions of the United States, Puerto Rico, and the U.S. Virgin Islands. (Digital Map). Reston, VA: U.S. Department of Agriculture, Forest Service.

Ciesla, W.M. 2000. Remote sensing in forest health protection. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Health Technology Enterprise Team. [Page nos. unknown].

Eastman, J.R. 2001. IDRISI 32: Guide to GIS and image processing. Vol. 2. Software Manual. Worcester, MA: Clark Labs, Clark University. [Page nos. unknown].

Eastman, J.R.; Jin, W.; Kyem, P.A.K.; Toledano, J. 1995. Raster procedures for multi-criteria/multi-objective decisions. Photogrammetric Engineering and Remote Sensing. 61(5): 539–547.

Krist, F.J., Jr. 2001. A predictive model of paleo-Indian subsistence and settlement. East Lansing, MI: Michigan State University. Ph.D. dissertation.

Krist, F.J., Jr. 2006. A tool for simulating hunter-gatherer decision making and behavior. In: Mehrer, M.W.; Wescott, K.L., eds. GIS and archaeological predictive modeling. Taylor & Francis: 335–353.

Lewis, J.W. 2002. Mapping risk from forest insects and diseases. FS-754. Washington, DC: U.S. Department of Agriculture, Forest Service. 3 p.

McRoberts, R.E.; Barbour, R.J.; Gebert, K.M. [and others]. 2006. Using basic geographic information systems functionality to support sustainable forest management decision making and post-decision assessments. Journal of Sustainable Forestry. 23(4): 13–34.

Mott, D.G. 1963. The forest and the spruce budworm. In: Morris, R.F. ed. The dynamics of epidemic spruce budworm populations. Memoirs of the Entomological Society of Canada. 31: 189–202.

Mowrer, H.T. 1992. Decision support systems for ecosystem management: An evaluation of existing systems. Gen. Tech. Rep. RM-296. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 145 p.

Reynolds, K.M. 1999. EMDS users guide (Version 2.0): Knowledge-based decision support for ecological assessment. Gen. Tech. Rep. PNW-470. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Station. 63 p.

Saaty, T.L. 1977. A scaling method for priorities in hierarchical structures. Journal of Mathematical Psychology. 15: 234–281.

Stein, S.M.; McRoberts, R.E.; Alig, R.J.; [and others]. 2005. Forests on the edge: housing development on America's private forests. Gen. Tech. Rep. PNW-636. Portland, OR: U.S. Department of Agriculture, Forest Service. 16 p.

Thatcher, R.C.; Barry, P.J. 1982. Southern pine beetle. Forest Insect and Disease Leaflet 49. Reston, VA: U.S. Department of Agriculture, Forest Service. [Not paged].

U.S. Department of Agriculture, Forest Service [USDA FS]. 2005. Forest insect and disease conditions in the United States 2004. Fort Collins CO: Forest Health Technology Enterprise Team. [Not paged].

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