A Multi-Criteria 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 common GIS-based multi-criteria approach that can account for regional variations in forest health concerns/threats. This framework, utilized 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 decision making. The national framework consists of a five step process designed to be highly iterative, utilizing input from a wide range of sources including subject area experts:

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.
5. Identify regions at risk of encountering a 25% 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 of 186 forest insect and disease models individually run and assembled into a National Map on a central server located at the Forest Health Technology Enterprise Team (FHTET) in Fort Collins, Colorado. The national framework, in which these models were constructed, also enables local knowledge and data to be entered into models allowing large-scale assessments to be

quickly conducted. This paper describes the framework developed during the construction of the National Insect and Disease Risk Map.

1. Introduction

Ensuring the health of America's forests requires the analysis, understanding, and management of complex and interrelated natural resources. Increasing use pressures on our forests, a continual threat from native and exotic insects and diseases (USDA 2005), and more complex management policies make natural resource management demanding. As a result, resource managers and policy makers require information beyond tabular summaries to assess where and how forest resources are being impacted. This is creating an increasing need for spatial-based decision support systems that can quickly summarize a wide range of tabular and geographic information, providing resource managers with clear, informed choices and, thereby, the ability to allocate human and financial resources more efficiently. Therefore, integrated and comprehensive approaches that use technologies, such as Geographic Information Systems (GIS), with the ability to concurrently analyze a large number of spatial variables, are important in the modern-day protection and management of our nation's forest resources (Ciesla 2000, McRoberts et al. 2006, Mowrer 1992, Stein et al. 2005, Reynolds 1999).

In 2000 the USDA Forest Service, State and Private Forestry Area, Forest Health Protection Unit (FHP) staff were asked to develop a GIS database of forest health risk on all forested lands in the United States (Lewis 2002). The Forest Health Monitoring Program (FHM) of the USDA Forest Service was asked by the FHP director to update this database in 2003 which resulted in a process that bears little resemblance to its parent effort. GIS methods, which include the introduction of an interactive multi-criteria risk assessment framework and resultant 1 kilometer resolution 2006 National Insect and Disease Risk Map (NIDRM), are significantly different in this "next generation" product.

The production of the 2006 risk map has been a highly collaborative process, coordinated by 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. Forest Service research and development was instrumental in the development of the host parameter data that drive individual models in the map.

The primary goal of the 2006 National Insect and Disease Risk Map is to develop a National communication tool that will provide Congress, USDA officials, and federal and state land managers with a periodic strategic assessment for risk of tree mortality due to major insects and diseases which is supported at the regional and state level. NIDRM is more than a map: it is an integration of 186 individual risk models constructed within a common consistent GIS-based multi-criteria framework that accommodates regional variations in current and future forest health conditions, knowledge, and data availability. The 2006 risk map process, utilized within the contiguous United States and Alaska, provides a repeatable, transparent process 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 modeling process is intended to increase the utilization of forest health risk maps within and outside the National Forest System.

The primary goal of this paper is to describe the framework developed for the construction of NIDRM and to briefly demonstrate how this process can be used to conduct assessments at multiple spatial scales.

2. The Assessment Framework

2.1. Defining Risk

The definitions surrounding risk and hazard in forest pest management are often confusing and contradictory. Historically, risk is described as the probability of harm from exposure to an agent (Kaplan 1997). Rather than trying to 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 and the probability of resulting tree mortality, defined as *susceptibility* and *vulnerability* respectively (Mott 1963). Characterizing the spatially explicit probability of insect and disease activity, however, requires spatially explicit quantitative data, frequently lacking at regional, national, and local levels. Therefore, we define risk as the *potential* for harm due to exposure from an agent(s). We also draw the distinction between susceptibility and vulnerability as Mott (1963) has, but in the context of potential rather than probability.

Measured as stand basal area[1] (BA) (Avery and Burkhart 2002) our threshold value for mapping risk is defined as the expectation that, without remediation, 25 percent or more of standing live BA on trees greater than 1 inch in diameter will die over the next 15 years due to insects and diseases.

2.2. A Conceptual Overview of a National Risk Assessment Framework

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

Forest pests, either non-native exotics that have not been established or cyclic native pests whose outbreaks occur sporadically about the landscape, disappearing from one region and reappearing in another, require that the modeler 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, whether a forest pest will always kill its host determines the next step. Once established, some risk agents (such as sudden oak death and chestnut blight) harm their hosts in the same way throughout the landscape regardless of existing site and stand conditions. This scenario generally applies to exotics, although some exotic pests (such as gypsy moth) produce mortality rates that may vary greatly depending on site and stand conditions. If a vulnerability assessment is not required (that is, pest effects are not site-dependent), then the susceptibility model can be used for the final risk assessment.

In cases (again, such as gypsy moth) where both susceptibility and vulnerability models are run, the interaction of these models creates the risk assessment. The degree to which 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, with agents such as gypsy moth 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 requiring only a vulnerability assessment, respectively. 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.

2.3. A GIS-Based Multi-Criteria 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 to enable the reader to focus on the process rather than the “correctness” of the example.) It should also be noted upfront 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 will be illustrated in the latter part of this paper. The accuracy of the model outputs does, however, depend on knowledge about forest

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[1] Sum of cross-sectional areas of tree steams measured at 4.5 feet above ground, expressed per land unit area.

pest behavior, the degree of informed personal judgment of the model developers, and the spatial accuracy and precision of the data driving the models.

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

2.3.1. Step 1: Identify Risk Agents and Host Species

Forest pest distributions are often limited to specific climatic and/or biophysical regimes. In addition, pest behavior and population dynamics often vary 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. Ecoregions capture broad climatic and biophysical patterns and, therefore, 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 non-endemic 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 both the construction of a susceptibility and vulnerability model (Figure 1).

2.3.2. Step 2: Identify, Rank, and Weight Criteria

After identifying risk agents and host species, the criteria (factors and constraints) that determine the potential for risk agent establishment and host vulnerability must be identified. For the risk assessment framework presented here we define:

- *Susceptibility* as the potential for introduction and establishment, over a 15-year period, of a forest pest within a tree species range.

- *Vulnerability* as the potential for experiencing mortality of a tree species at a maximum realizable mortality rate over a 15 year period *if* a forest pest were to become established.

Regions that are both very susceptible to a pest attack and highly vulnerable to its effects (often trees that are weakened or stressed) 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. Areas will not experience mortality from a risk agent regardless of how vulnerable trees are at any given location if these same regions are not susceptible to attack. Therefore, susceptibility also acts as a constraint. Constraints are criteria that must be met for susceptibility and vulnerability potential to occur at any given location. The maximum realizable mortality rate for our hypothetical risk agent X is 100 percent. Therefore 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, and
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) (Avery and Burkhart 2002), and
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 while 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 representing the distribution and intensity of each insect and disease that contributes to the mortality in any given area. This layer(s) is then used as a criterion in the susceptibility or vulnerability models of the primary risk agent depending on whether the additional agent(s) contributes to an increased risk of establishment and/or mortality. Due to the lack of understanding of the interactive affects between 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 affects of risk agents were understood we could model them under this current framework.

The relative importance of each criterion, or rank, for determining whether an area (pixel) has the potential to be susceptible and vulnerable to a risk agent is entered into a pairwise comparison matrix. 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 every criterion (Table 1). The resultant weights, expressed as percent 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, and a matrix is not needed if only a single criterion is present.

A pairwise comparison matrix is a robust method for assessing the comparative importance of factors (Saaty 1977, Eastman et al. 1995, Eastman 2001). It is particularly useful when attempting to derive weight evaluations for multiple criteria under many considerations.

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 et al. 1995, Eastman 2001). 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, and therefore it receives a value of 1/3 in the comparison matrix while BA receives a value of 1. Soil dryness/wetness is of strongly less importance to BA and is assigned a value of 1/5.

The 10-point rating system enables forest health specialists to select the most important factor or factors and compare the remaining criteria to it. All these criteria have a positive influence and therefore 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 automatically calculate weights. The weights in the spreadsheet are calculated by summing all the rank values and then dividing each rank by that sum. Having the ability to calculate weights automatically enables the user to see changes in weights immediately as ranks are adjusted.

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

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

2.3.3. 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. The RMIT choose an evaluation scale ranging from 0 to 10. Using this scale, a criterion value of 0 represents little or no potential while a value of 10 exhibits the highest potential. 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.

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

An integer scale ranging from 0 to 10 was chosen for simplicity and due to the lack of precise data layers and/or models in many instances at the national level. At a finer resolution and with more precise data, an extended standard scale may be of more use—for example, 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. When the transition from criterion values with potential to values without potential is gradual, standardization of criteria values is not an easy task. Consider the BA criterion in our example: potential for vulnerability to pest X ends or is very low when stocking levels are at or below 20 square feet and increase gradually until reaching stocking levels of 120 square feet. Rather than manually breaking this range into ten discrete classes, a fuzzy membership (Eastman et al. 1995, Eastman 2001) set can be used to automatically stretch or assign a continuous set of values. A second advantage of selecting a fuzzy membership is that the data can be assigned standardized values in differing ways depending 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 on the graphs in Figure 3, or inflection points, 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 while ***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.

ArcView 3.x Spatial Analyst 2.x Model Builder does not contain a routine that will automatically recode or stretch criterion values according to a fuzzy membership. As a result, a worksheet was developed to calculate break points that could be manually entered into the RECLASS module of Model Builder (Figure 4), dividing the values into ten 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, 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):

$$P = \sum w_i x_i \qquad 1.$$

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 ranging 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 is 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 is for a tree species to experience mortality over the next 15 years.

Model Builder 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.

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

Using a standardized scale of 0 - 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, then the host species in this 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, while a pixel with a value of 5 would get 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 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 that model results do not guarantee that mortality will occur at any given location; rather they suggest the *potential* for loss. The resultant map of BA loss for Risk agent X is depicted in Figure 5.

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

$$D = 1 – (1-p1)(1-p2)(1-p3)... (1-pn) \qquad 2.$$

where D = Total Proportionate Mortality

p1 = Proportionate Mortality Caused by Agent 1

n = nth Agent

In the example above where two agents cause 75% mortality 94% of the total BA would be lost in that pixel:

$D = 1 – (1- p1)(1-p2)$

$D = 1 – (1- 0.75)(1-0.94)$

$D = 0.985$

We realize this mechanism does not address complex interactions between various pests. The body of literature regarding pest interactions is limited and therefore the basic understanding of cumulative impacts is not understood enough to model complex interactions at this time.

2.3.5. Step 5: Identify Regions at Risk

Estimates of potential 15 year BA loss compiled for all risk agents, in Step 4, was divided by a surface representing total BA to calculate the percent of total BA that might be lost in each pixel. Pixels where the total loss exceeded or met 25 percent of the total BA, were flagged for the national composite risk map (NIDRM). Since the original percentages are available, different threshold values for risk can be defined and mapped. Also, risk due to individual pest species by host were rendered as well.

2.4. Modeling at Multiple Scales/Resolutions

Once a model has been constructed in ArcView 3.x Spatial Analyst 2.x Model Builder, models can easily be re-run at multiple scales. GIS layers can be swapped in and out of Model Builder 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 (Thatcher and Barry 1982) model run at 3 different resolutions (1 kilometer, 250, and 30 meter). The 30-meter resolution model includes an additional criterion depicting forest stand connectivity.

3. 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, all models being assembled into a national composite (NIDRM) (Figure 9). Given the nature of our assignment; that is to construct a national 15 year assessment of forest health risk due to insects and diseases we believe that NIDRM is successful due to the following characteristics. NIDRM 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 framework 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 through which to conduct risk assessments. Within this framework, forest health specialists are able to determine why any area is at risk, what the source data are, and how the model(s) for that region were constructed, thus well documenting any models comprising 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 and/or as additional data and models become available. Scalability enables subject area experts to conduct both local and regional assessments using an identical framework; ensuring national products do not conflict with local knowledge.

4. Efficacious - When developing a framework, the need for efficiency, precision, accuracy, and usability must all be considered. A national risk map product with potentially hundreds of models behind it requires a highly efficient modeling process, but also 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 easily interpreted results and detailed model documentation.

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 has ensured that regional comparisons can be made. Without standardization, NIDRM would be little more than a federation of maps with little or 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 due to 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), forest fire risk, etc.

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5. Tables

Table 1--Sample weights for vulnerability to risk agent X.

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

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

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	1/7
	1/8
Extremely Less	1/9
	1/10
Unsuitable	N/A

Table 3--Rankings for BA using linear and sigmoidal memberships.

Fuzzy memberships enable values to be recoded in a variety of ways to capture relationships between insect and disease behavior and criteria. This example demonstrates the affects of two commonly used memberships on BA. A value of 10 represents the highest potential for risk with a value of 0 representing the lowest.

BA	Rank (Linear)	Rank (Sigmoidal)
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

6. Figures

Note to editor: figures have been placed here for reference purposes. Full-scale figures are attached in a separate folder.

Figure 1--Risk assessment framework.

Provides a conceptual overview of the multi-criteria risk assessment framework used to construct the 2006 National Insect and Disease Risk Map (NIDRM).

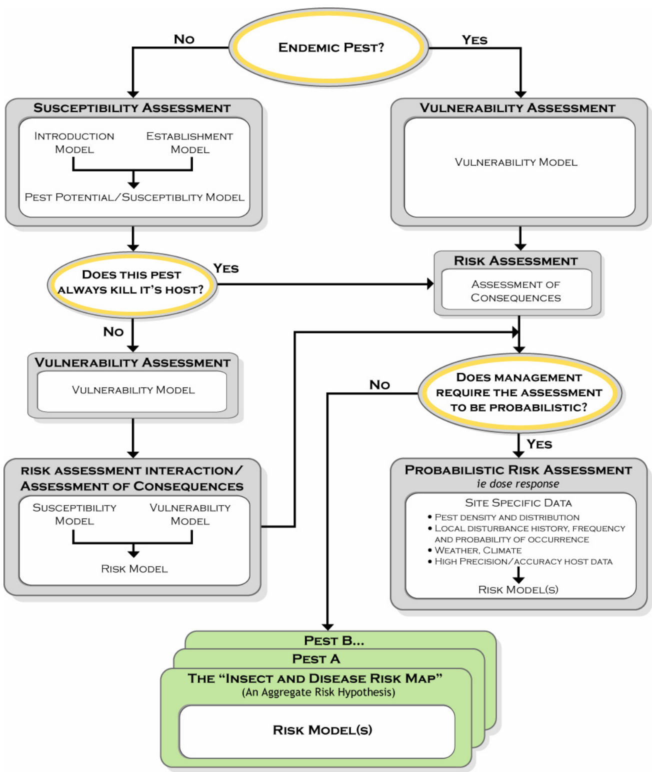


Figure 2--Spreadsheet template.

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

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)	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

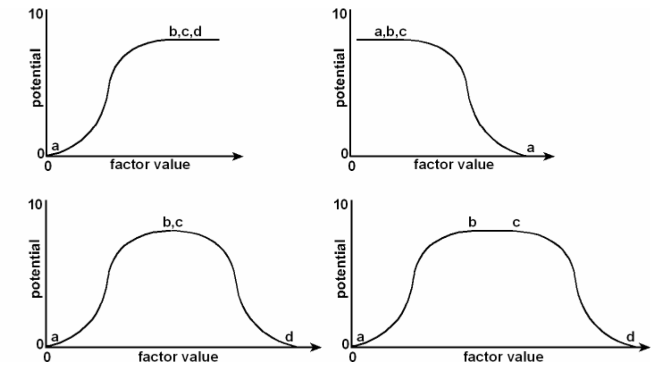
Rank/Weight 1 50%	Criterion	Risk Begins (a)	Risk Peaks (b)	Decreases (c)	Risk Ends (d)	Curve	Rank	Weight
Criteria 1	Aspen BA (sq. ft./acre)	20	120	120	120	Linear	1	65%
Criteria 2	Aspen QMD (in.)	0	10	10	10	Linear	1/3	22%
Criteria 3	Soil Dryness/Wetness	20	20	20	50	Linear	1/5	13%
Criteria 4								
Criteria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

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

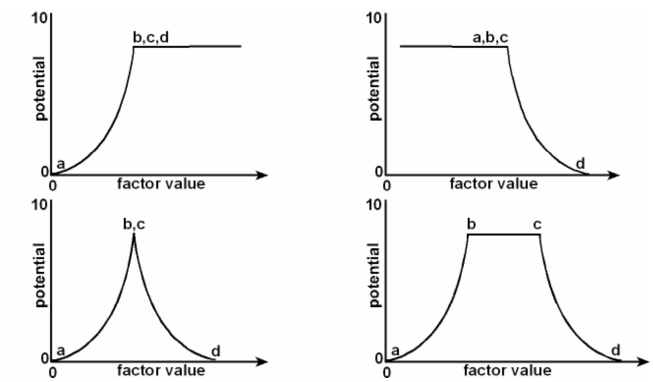
Figure 3--Fuzzy Memberships.

Available fuzzy memberships include a) sigmoidal functions, b) J-functions, and c) linear functions. Custom functions can also be developed depending on the relationship of the data to potential risk.

a



b



c

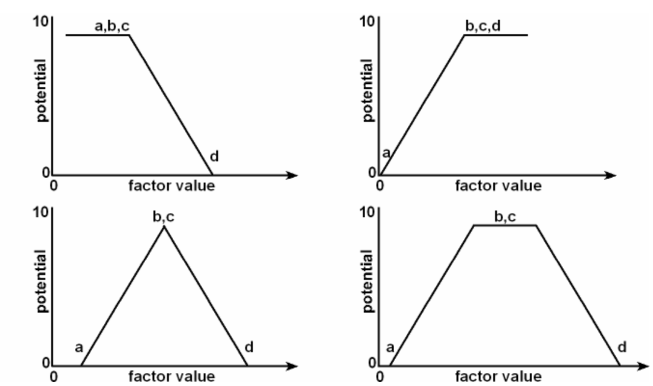
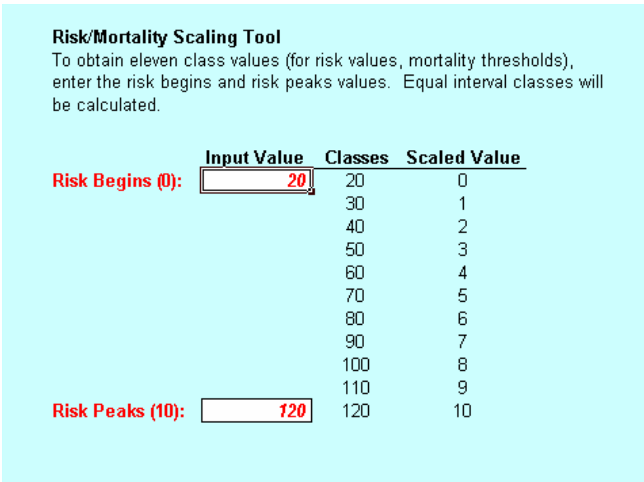


Figure 4--Criteria ranking tool and RECLASSIFICTION module in Model Builder.

The criteria ranking tool divides factor values into classes that can be entered into Model Builder using the RECLASSIFICTION module.



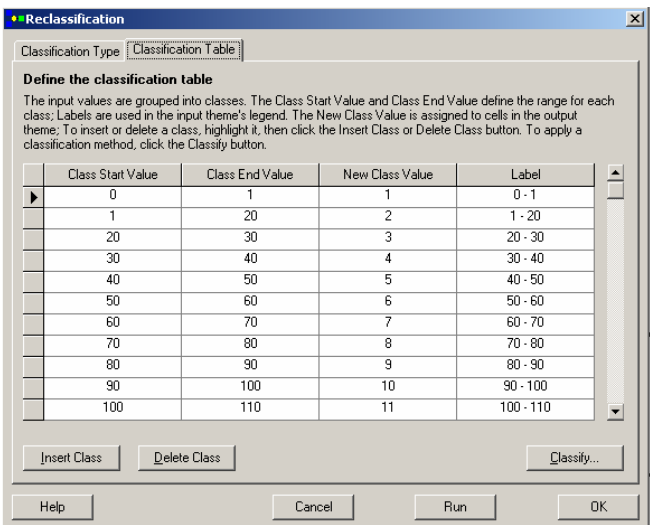


Figure 5--Sample criteria maps and resultant model outputs.

All criteria used in the risk agent X model are show below with their corresponding weights. Notice how each layer affects the outcome. Arrows show the direction of flow during model construction.

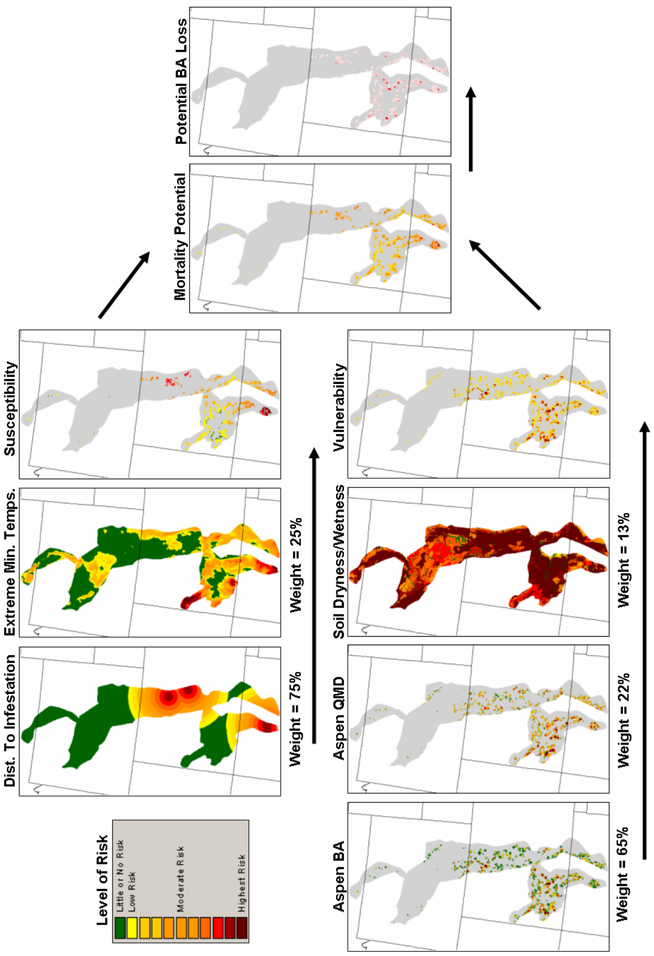


Figure 6--Weighted overlay diagram.

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

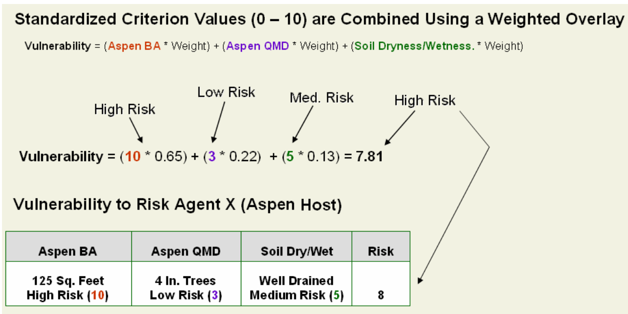


Figure 7--WEIGHTED OVERLAY module.

The Model Builder WEIGHTED OVERLAY module provides a "user friendly" interface in which criteria can be combined in a multi-criteria model. This module also provides a means of documenting model information and can be used to rapidly re-run a model using various weights and ranks.

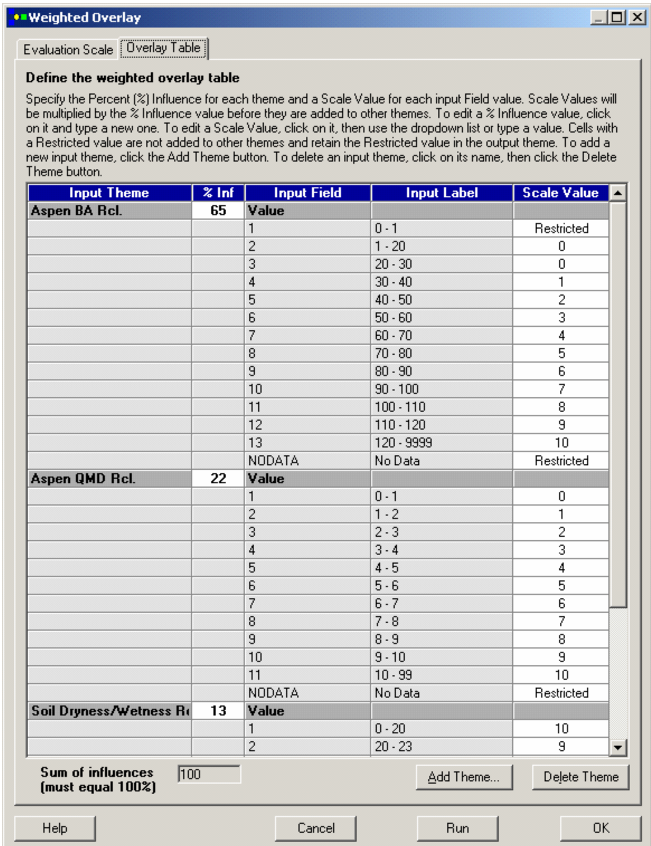
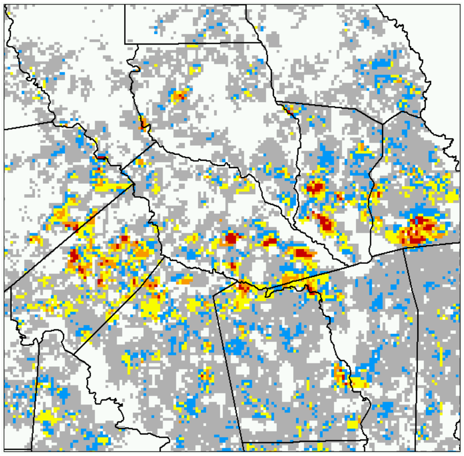


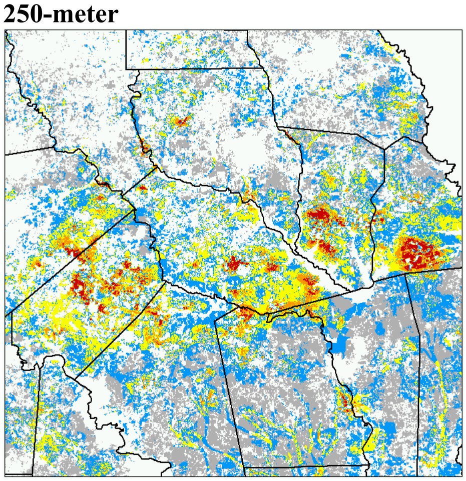
Figure 8--Southern pine beetle risk models.

Each map depicts the potential for southern pine beetle mortality in a portion of east Texas with red representing extreme risk, orange high, yellow medium, and blue low.

1-kilometer



250-meter



30-meter

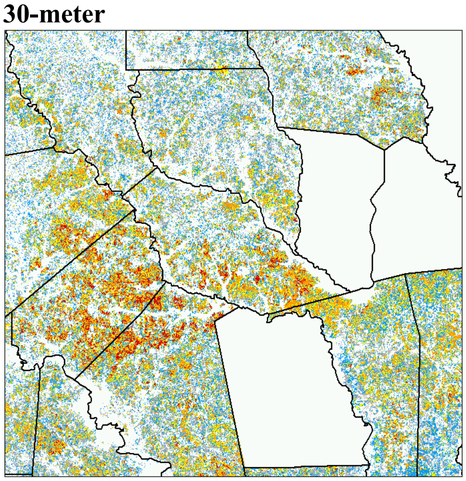


Figure 9--2006 National Insect and Disease Risk Map (NIDRM) for the United States.

NIDRM characterizes the potential for significant losses (at or above 25%) of total forest basal area (BA) spatially and encompasses approximately 58 million acres.