A Multi-Criteria Framework for Producing Local, Regional, and National Insect and Disease Risk Maps (Draft)

Frank J. Krist, Jr.
USDA Forest Service
Forest Health Technology Enterprise Team (FHTET)
2150 Centre Ave., Bldg. A Suite 331
Fort Collins, CO 80525-1891
970-295-5845
E-Mail: fkrist@fs.fed.us

Frank J. Sapio
USDA Forest Service
Forest Health Technology Enterprise Team (FHTET)
2150 Centre Ave., Bldg. A Suite 331
Fort Collins, CO 80525-1891
970-295-5840
E-Mail: fsapio@fs.fed.us

Borys M. Tkacz
USDA Forest Service
Forest Health Monitoring
RPC, 7th Floor (FHP)
1601 North Kent Street,
Arlington, VA 22209
703-605-55343
E-Mail: btkacz@fs.fed.us

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, multi-criteria approach for insect and disease risk mapping that can account for regional variations in forest health concerns and threats. This risk mapping 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 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.

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 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. This paper describes the development of this.

Key Words: risk map, insect and disease risk, NIDRM, multi-criteria modeling, GIS, forest health monitoring

1.   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 2005), and more complex management policies make natural resource management demanding. In order to accurately assess where and how forest resources are being impacted, resource managers and policy makers 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 its 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 et al. 2006, Mowrer 1992, Stein et al. 2005, Reynolds 1999).

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 policy makers, USDA officials, and federal and state land managers with a periodic, strategic assessment for risk of tree mortality due to major insects and diseases. NIDRM 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 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 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 Protection Unit (FHP). 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

1   assist in model development. Even though the goal of this paper is to describe the GIS framework developed for the

2   construction of NIDRM and to briefly demonstrate how this process can be used to conduct assessments at multiple

3   spatial scales, the authors want to emphasize the importance of a team approach that ensures participation from local

4   resource managers.

5   2.   The Assessment Framework

6   2.1. Defining Risk

7   The definitions for "risk" and "hazard" in forest pest management can be confusing and contradictory. Rather than

8   reconcile the various definitions of risk and hazard we use the following construct.

9   When assessing risk as it relates to forest health, risk is often composed of two parts; the probability of a forest

10   being attacked *susceptibility)* and the probability of resulting tree mortality (*vulnerability)* (Mott 1963).

11   Characterizing the spatially explicit probability of insect and disease activity requires spatially explicit quantitative

12   data. However, because such data are often lacking at regional, national, and local levels, we define risk as the

13   *potential* for harm due to exposure to an agent(s). Also, we draw the distinction between susceptibility and

14   vulnerability (Mott 1963), but in the context of potential rather than probability.

15   Measured as stand basal area[1] (BA) (Avery and Burkhart 2002) our threshold value for mapping risk is defined as

16   the expectation that, without remediation, over the next 15 years 25 percent or more of standing live BA on trees

17   greater than 1 inch in diameter will die due to insects and diseases. The threshold value for mapping insect and

18   disease risk is independent of the GIS framework discussed in the remainder of this paper. Therefore, the framework

19   can support any threshold.

20   2.2. A Conceptual Overview of a National Risk Assessment

21   Framework

22   Figure 1 provides a conceptual overview of the risk-assessment process discussed here. The modeler first indicates

23   whether the forest pest under study is endemic or not. If a pest is established throughout a region, then the potential

24   or source for actualized harm is assumed to be equal everywhere and all host material is susceptible. In such cases,

25   susceptibility assessments are not required. If a mechanism or dataset exists that addresses varying pest densities in

26   time and space, we can accommodate those densities within our framework. However, few national datasets for pest

27   density exist, and we assume presence or absence in our modeling scenarios. A vulnerability model, which

28   determines the likelihood and extent to which trees will be harmed by the pest of concern within the defined

29   timeframe of 15 years, is required to complete a risk assessment in a case where a pest is already established, .

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

When considering forest pests, either non-native 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 and chestnut blight, harm their hosts in the same manner throughout the landscape, regardless of existing site and stand conditions. This applies to exotics and native species, alike, although some exotic pests, such as gypsy moth, produce mortality rates that can vary 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, both susceptibility and vulnerability receive equal influence, and risk agents such as sudden oak death and mountain pine beetle 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.

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, 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.

Due to its availability from state and Federal agencies, ease of use, and relative stability, ArcView 3.x® Spatial Analyst 2.x® Model Builder® was selected as the software for the multi-criteria framework. In addition, previous familiarity with Spatial Analyst 2.x® among GIS specialists greatly reduced the rollout time 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, was developed within the Forest Service

to support local and regional decision making, and provides a framework for conducting knowledge-based ecological assessments.

2.3.1.   Step 1: Identify Risk Agents and Host Species

Often, forest pest distributions are 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. Because ecoregions capture broad climatic and biophysical patterns and, 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 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 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 a tree species range.

- *Vulnerability* as the potential (rather than probability) 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 (e.g., 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. 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   1. Distance to known infestations

2   2. Average annual minimum extreme temperature.

3   3. Aspen host presence, with the latter criterion acting as a constraint.

4   Factors for vulnerability are:

5   1. Aspen BA.

6   2. Aspen quadratic mean diameter (QMD) (Avery and Burkhart 2002).

7   3. Soil dryness/wetness.

8   Although risk agent X requires both a susceptibility and vulnerability model for its risk assessment, recall that risk

9   assessments for some pests require only one or the other.

10 Many forest pests invariably cause tree mortality while others only contribute to their demise. Stressors often work

11 in concert to cause mortality. Modeling pest complexes that may work together to cause mortality requires a layer

12 (or layers) representing the distribution and intensity of each insect and disease that contributes to the mortality in

13 any given area. Depending on whether the additional agent(s) contributes to an increased risk of establishment

14 and/or mortality, this layer is then used as a criterion in the susceptibility or vulnerability models of the primary risk

15 agent. Due to the lack of understanding of the interactive affects among multiple stressors, we treat interactions as

16 additive. The exception to this is where we use one pest risk model to constrain the other. If the interactive effects of

17 risk agents are understood we can model them under this current framework.

18 The relative importance of each criterion, or rank, for determining whether an area, or pixel, has the potential to be

19 susceptible and vulnerable to a risk agent is entered into a pairwise comparison matrix. A pairwise comparison

20 matrix is a robust method for assessing the comparative importance of factors (Saaty 1977, Eastman et al. 1995,

21 Eastman 2001). It is particularly useful when attempting to derive weight evaluations for multiple criteria under

22 many considerations. Every possible pairing of factors must be identified and entered into the matrix, ordering the

23 criteria most important to least important. The matrix is used to generate a set of weights representing the relative

24 importance of each criterion (Table 1). The resultant weights, expressed as percent influence, must sum to 1 (or 100

25 percent) and are used to combine criteria values within a weighted overlay (see Step 3). Separate matrices are

26 generated for both susceptibility and vulnerability. A matrix is not needed if only a single criterion is present.

27 Prior to entering values into the pairwise matrix, comparisons must be made between criteria using a 10-point

28 continuous rating scale (Table 2) modified by Krist (2001, 2006) from the 9-point scale Eastman uses in the IDRISI

29 software (Eastman et al. 1995, Eastman 2001). Rankings in Table 2 represent the relative importance of each

30 criterion. For example, QMD is moderately less important than BA for determining the vulnerability potential to risk

31 agent X; therefore, QMD receives a value of 1/3 in the comparison matrix while BA receives a value of 1. Soil

32 dryness/wetness is of strongly less importance to BA and is assigned a value of 1/5.

1   The 10-point rating system enables forest health specialists to select the most important factor(s) and compare the

2   remaining criteria to it (them). All these criteria have a positive influence and contribute to potential. The negative

3   impacts of a criterion can be accounted for by reversing the rankings for the criterion values, thus turning a negative

4   relationship into a positive one (one that contributes to potential).

5   We simplified the workload of regional forest health specialists constructing models by enabling the spreadsheet

6   (Figure 2) used to collect model information to simulate the comparison matrix developed by Saaty (1977) and to

7   calculate weights automatically. Having the ability to calculate weights automatically enables the user to see

8   changes in weights immediately as ranks are adjusted. The weights in the spreadsheet are calculated by first

9   summing all the rank values and then dividing each rank by that sum.

10 In addition to weighting risk agent criteria, weights must be assigned to susceptibility and vulnerability, based on

11 their importance in determining the potential for a tree species to experience the maximum realizable mortality rate

12 from the pest of concern in the next 15 years. These weights are used to combine the resultant susceptibility and

13 vulnerability models in the final risk assessment (see Step 3). In the case of risk agent X, equal weight (50 percent)

14 was given to both susceptibility and vulnerability. Remember that susceptibility acts as a constraint in the final risk

15 assessment; areas with no possibility of being susceptible in the next 15 years are not at risk.

16 Criteria, rankings, and weights for risk agent models can be selected in a number of ways. Ideally, if data on the

17 distribution and intensity of a risk agent exist, statistical analyses may be performed in the hopes of identifying

18 relationships between risk agent activity and forest and biophysical attributes, as represented in GIS layers. If such a

19 relationship is found, the strength of the correlation can be used to determine weights. Unfortunately, this data-

20 driven or literature/research-based approach is not always possible, because in many instances data on risk agent

21 distributions, intensity, and behavior are either inadequate and/or incomplete. In such instances, modelers must rely

22 on informed professional judgment and/or expert opinion when selecting criteria and weights.

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

24 2.3.3.   Step 3: Standardize Criteria Values and Combine the
25 Resultant Maps

26 With the risk agent criteria and their corresponding GIS layers identified and weights generated for susceptibility

27 and vulnerability, the factor values must be standardized, based on a common evaluation scale. Standardization

28 allows for the comparison of criteria with differing values, such as BA, with units of square feet per acre and QMD,

29 with units in inches. An evaluation scale from 0 to 10, with 0 representing little or no potential, and 10 representing

30 the highest potential was chosen. For example, in the case of risk agent X, higher stocked stands are more

31 vulnerable; therefore, areas with stocking levels approaching 120 square feet or more are given a value of 10 (Table

32 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

1   criterion does not eliminate the possibility for risk to occur. If other criteria have values greater than 0, potential is

2   still possible at a location.

3   Regions without aspen are constrained. Constraints do not need to be standardized, but they do restrict modeled

4   potential to specific areas, such as regions containing aspen or areas within a certain distance of current risk agent

5   infestations. Because of the restrictions, the potential for risk can be precluded in some areas, regardless of the

6   strength of the other criteria.

7   For simplicity, and due to the frequent lack of precise data layers and/or models at the national level, an integer scale

8   from 0 to 10 was chosen. At a finer resolution and with more precise data, an extended standard scale may be of

9   more use. e.g., an integer scale of 0 to 100 would capture a wider range of variation in the data.

10   A standard scale may be applied to a GIS data set through a manual recoding of the criterion values. This is

11   particularly easy to do when data have sharp boundaries and discrete classes. However, this is not an easy task when

12   the transition from criterion values with potential to values without potential is gradual. Consider the BA criterion in

13   our example. Potential for vulnerability to pest X ends or is very low when stocking levels are at or below 20 square

14   feet and increases gradually until stocking levels reach 120 square feet. Rather than manually break down this range

15   into ten discrete classes, a fuzzy membership set (Eastman et al. 1995, Eastman 2001) can be used to stretch or

16   assign a continuous set of values, automatically. Another advantage to selecting a fuzzy membership is that the data

17   can be assigned standardized values in differing ways, depending on how potential varies within a criterion. The

18   most common method of assigning values based on fuzzy membership is a simple linear stretch, in which potential

19   increases linearly. However, if potential rises gradually and then accelerates and tapers off, a sigmoidal function

20   may capture the natural variation more precisely.

21   Twelve fuzzy membership functions were used in the construction of NIDRM models, including linear, sigmoidal,

22   and J-shaped functions (Figure 3). Table 3 shows the difference between the resultant values of a linear and

23   sigmoidal stretch, the most common memberships used during the production of NIDRM. The letters (inflection

24   points) on the graphs in Figure 3 represent where risk potential *a)* begins, *b)* peaks or reaches its highest, *c)* begins to

25   decrease (though this may or may not happen), and *d)* ends or no longer changes (levels off). In the risk agent X

26   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

27   descriptions on the column headers of the spreadsheet in Figure 2 and the Curve column, where a fuzzy membership

28   (curve) is chosen for each criterion.

29   ArcView 3.x® Spatial Analyst 2.x® Model Builder® does not contain a routine that will automatically recode or

30   stretch criterion values according to a fuzzy membership, so a worksheet was developed to calculate break points

31   that could then be manually entered into the RECLASS module of Model Builder (Figure 4), effectively dividing the

32   values into eleven classes. Values for each risk agent's criteria were manipulated in Model Builder in this way.

33   Figure 5 illustrates what a set of standardized GIS layers would look like for the central Rocky Mountains using risk

34   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):

$$P = \sum w_i x_i$$

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.

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 –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, while 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 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 can not be added up to calculate total BA losses. For example, if one agent attacks a resource and has the potential to kill 75% of the trees and another agent attacks the same resource in the same area and may kill 75% of the trees, it is incorrect to say that up to 150% 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:

1    $D = 1 - (1-p1)(1-p2)(1-p3)... (1-pn)$

2   **where:**

3   **D = Total Proportionate Mortality**

4   **p1 = Proportionate Mortality Caused by Agent 1**

5   **n = nth Agent**

6   In the example above where two agents may each cause 75% mortality, 94% of the total BA would be lost in that

7   pixel when total losses are calculated using the simplifying assumption:

8    $$D = 1 - (1- p1)(1-p2)$$

9    $$D = 1 - (1- 0.75)(1-0.75)$$

10    $$D = 0.9375 \text{ or } 94\%$$

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

12   regarding pest interactions is limited, so the basic understanding of cumulative impacts is not understood well

13   enough to model complex interactions.

14   ### 2.3.5.   Step 5: Identify Regions at Risk

15   To calculate the percent of total BA that might be lost in each pixel, estimates of potential 15-year BA loss compiled

16   for all risk agents in Step 4 were divided by a surface representing total BA. Pixels where the total loss exceeded or

17   met 25 percent of the total BA were flagged for the national composite risk map (NIDRM). Because the original

18   percentages are available, different threshold values for risk can be defined and mapped. Risk due to individual pest

19   species by host also were provided.

20   ## 2.4. Modeling at Multiple Scales/Resolutions

21   Once a model has been constructed in ArcView 3.x® Spatial Analyst 2.x® Model Builder®, models can be re-run at

22   multiple scales. GIS layers can be swapped in and out of Model Builder with little or no modification when standard

23   measurement units exist across scales. As additional data become available at finer scales, supplementary criteria

24   can be added to the model. Figure 8 shows the same southern pine beetle (Thatcher and Barry 1982) model run at 3

25   different resolutions (1 kilometer, 250, and 30 meter). The 30-meter-resolution model includes an additional

26   criterion depicting forest stand connectivity.

27   # 3.   Discussion/Conclusions

28   The 2006 national risk assessment employed 186 risk-agent models representing over 50 risk agents acting on 61

29   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 due to insects and diseases, we believe that NIDRM is successful, because: 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 to conduct risk assessments. 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 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 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 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).

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8   5.   Tables

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

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

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

11   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

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

14   Fuzzy memberships enable values to be reclassed or recoded in a variety of ways to capture relationships between

15   insect and disease behavior and criteria. This example demonstrates the affects of two commonly used memberships

16   on BA, with 10 representing the highest potential for risk..
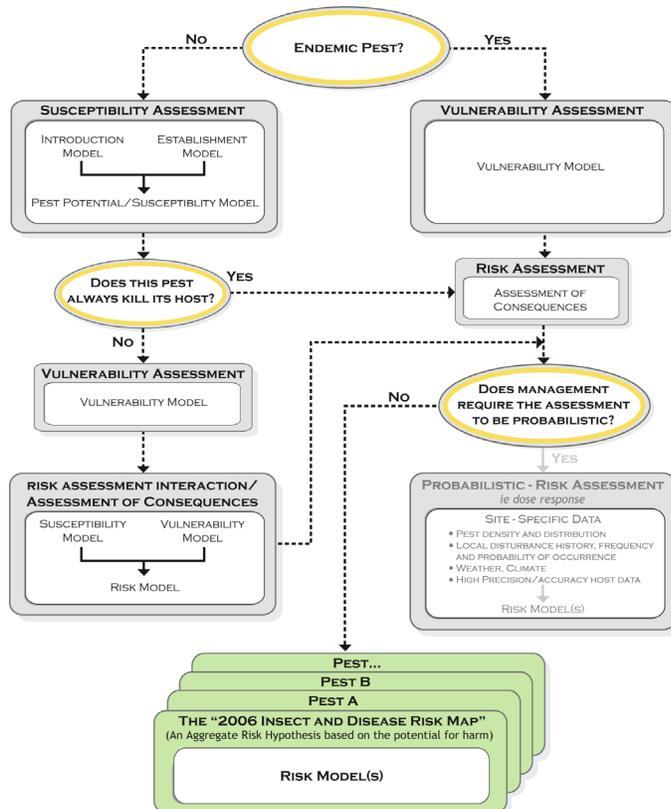
17

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

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6.   Figures

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		Criterion	Risk Begins (a)	Risk Peaks (b)	Decreases (c)	Risk Ends (d)	Curve	Rank	Weight
1	50%								
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		Criterion	Risk Begins (a)	Risk Peaks (b)	Decreases (c)	Risk Ends (d)	Curve	Rank	Weight
1	50%								
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	

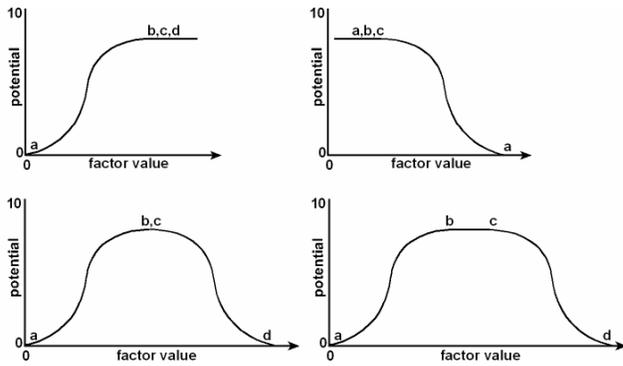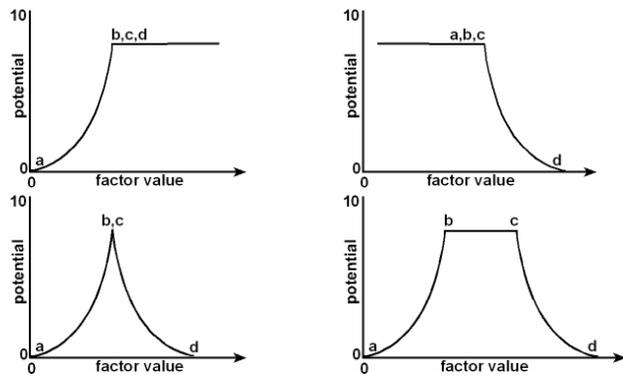| Citations	2, 8, 15	Model Certainty	4 - Expert Opinion

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Figure 3--Fuzzy Memberships

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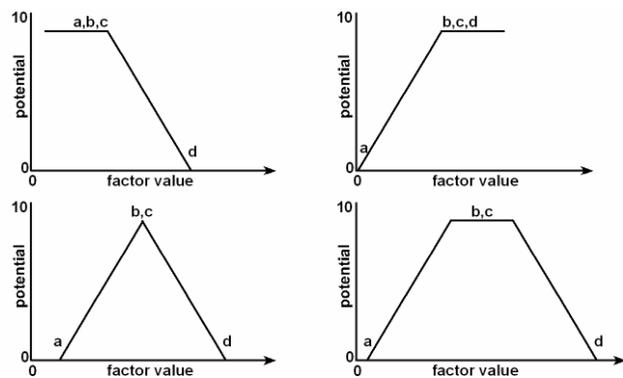functions can be developed, based on the relationship of the data to potential risk.

a

b

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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.

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8 **Figure 5--Sample criteria maps and resultant model outputs**

9 All criteria used in the risk agent X model are shown below with their corresponding weights. Notice how each layer

10 affects the outcome. Arrows show the direction of flow during model construction.
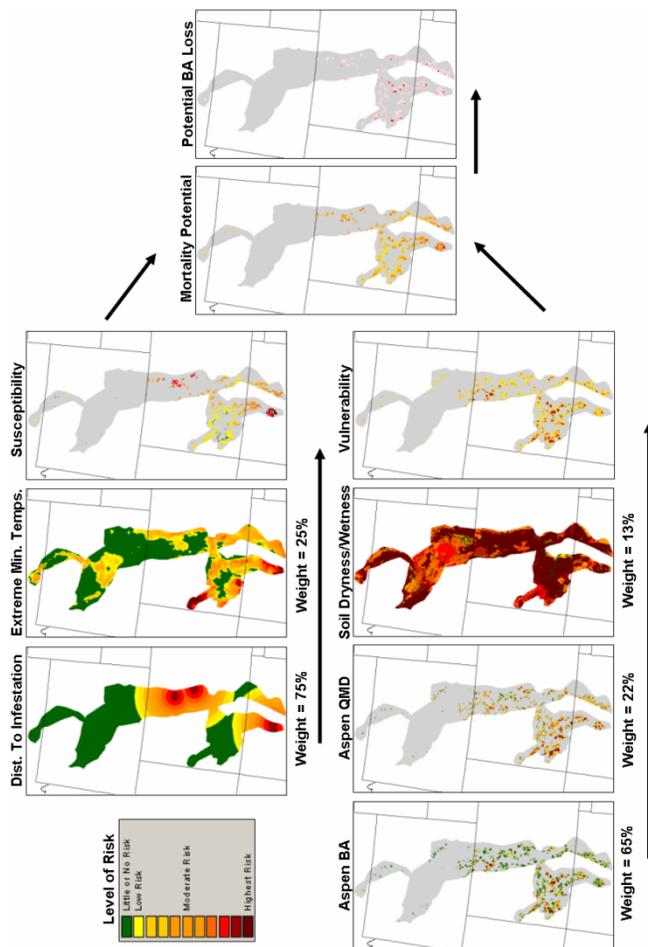
11

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1 **Figure 6--Weighted overlay diagram**

2 Weighted overlay for the risk agent X vulnerability model. Notice how much influence the relatively high weight for

3 BA has on the final model outcome.

Standardized Criterion Values (0 – 10) are Combined Using a Weighted Overlay

Vulnerability = (Aspen BA * Weight) + (Aspen QMD * Weight) + (Soil Dryness/Wetness. * Weight)

High Risk   Low Risk   Med. Risk   High Risk

Vulnerability = (10 * 0.65) + (3 * 0.22) + (5 * 0.13) = 7.81
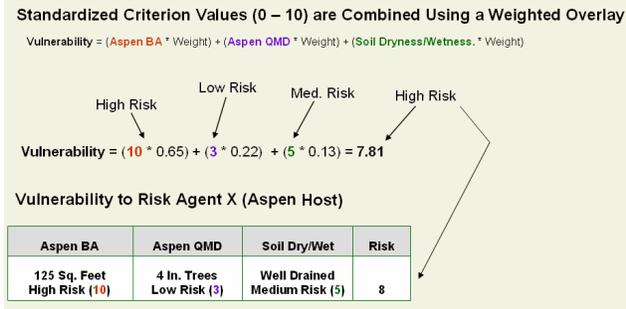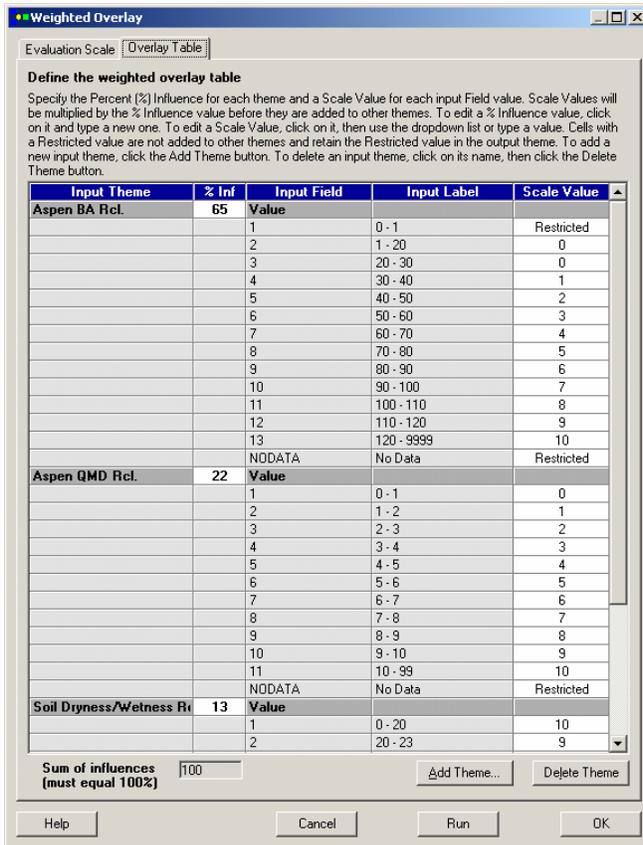
Vulnerability to Risk Agent X (Aspen Host)

Aspen BA	Aspen QMD	Soil Dry/Wet	Risk
125 Sq. Feet High Risk (10)	4 In. Trees Low Risk (3)	Well Drained Medium Risk (5)	8

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6 **Figure 7--WEIGHTED OVERLAY module**

7 The Model Builder weighted overlay module provides a "user friendly" interface in which criteria can be combined

8 in a multi-criteria model. This module also provides a means of documenting model information and can be used to

9 re-run a model using various weights and ranks.

Weighted Overlay

Evaluation Scale | Overlay Table

Define the weighted overlay table

Specify the Percent (%) Influence for each theme and a Scale Value for each input Field value. Scale Values will be multiplied by the % Influence value before they are added to other themes. To edit a % Influence value, click on it and type a new one. To edit a Scale Value, click on it, then use the dropdown list or type a value. Cells with a Restricted value are not added to other themes and retain the Restricted value in the output theme. To add a new input theme, click the Add Theme button. To delete an input theme, click on its name, then click the Delete Theme button.

Input Theme	% Inf	Input Field	Input Label	Scale Value
Aspen BA Rcl.	65	Value		
		1	0 - 1	Restricted
		2	1 - 20	0
		3	20 - 30	0
		4	30 - 40	1
		5	40 - 50	2
		6	50 - 60	3
		7	60 - 70	4
		8	70 - 80	5
		9	80 - 90	6
		10	90 - 100	7
		11	100 - 110	8
		12	110 - 120	9
		13	120 - 9999	10
		NODATA	No Data	Restricted
Aspen QMD Rcl.	22	Value		
		1	0 - 1	0
		2	1 - 2	1
		3	2 - 3	2
		4	3 - 4	3
		5	4 - 5	4
		6	5 - 6	5
		7	6 - 7	6
		8	7 - 8	7
		9	8 - 9	8
		10	9 - 10	9
		11	10 - 99	10
		NODATA	No Data	Restricted
Soil Dryness/Wetness Rc	13	Value		
		1	0 - 20	10
		2	20 - 23	9

Sum of influences (must equal 100%) [100]

Add Theme...   Delete Theme

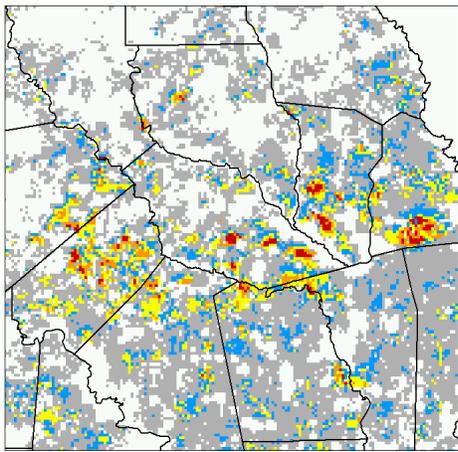Help   Cancel   Run   OK

10

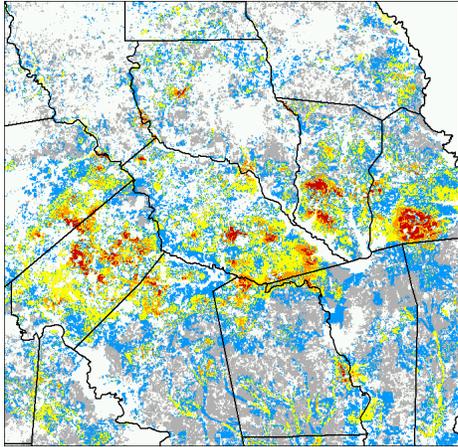1

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13 **Figure 8--Southern pine beetle risk models**

14 Each map depicts the potential for southern pine beetle mortality in a portion of east Texas. Red represens extreme

15 risk, orange high, yellow medium, and blue low.
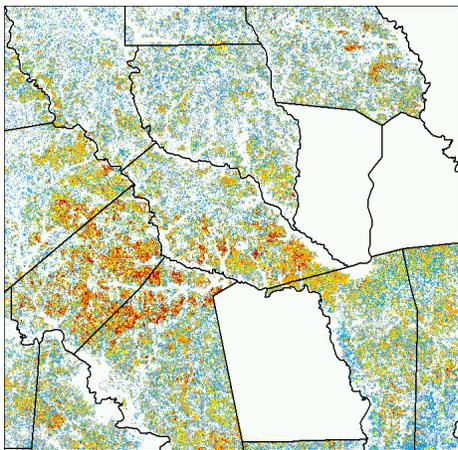
16 **1-kilometer**

17

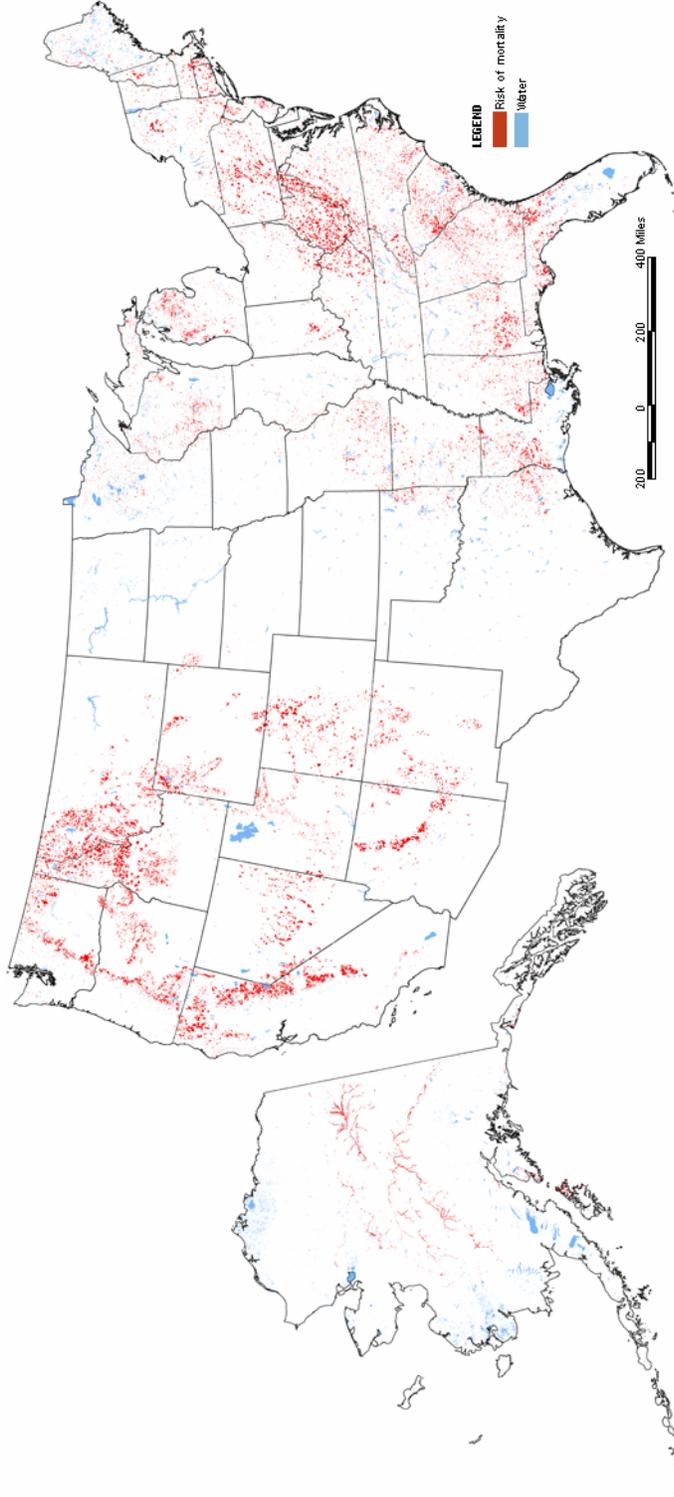18 **250-meter**

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2   **30-meter**

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

5   **States**

6   NIDRM characterizes the potential for significant losses (at or above 25%) of total forest basal area (BA), spatially.

LEGEND
Risk of mortality
Water

200 0 200 400 Miles

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