"Red-tailed hawk nests are in trees greater than 20 cm dbh and the optimum nest locations are in trees greater than 50 cm dbh."

(2) Describe relationships between variables. There are many possible relationships between variables. Four relationships that are commonly used in HSI models are described below.

(a) Limiting factors. This relationship is used when the variable with the lowest suitability is perceived to be so significant that it overrides all other factors in the functional relationship. For example, this relationship can be expressed verbally as:

"The overall habitat suitability for the red-tailed hawk is the suitability for reproduction or the suitability for cover or the suitability for food whichever is the smallest."

(b) Cumulative relationships. Cumulative or additive relationships are appropriate in circumstances where a threshold exists which can be met by any one, or a combination of, variables. For example, this relationship can be expressed verbally as:

"Reproductive habitat for red-tailed hawks is composed of the number of trees > 50 cm dbh plus rocky cliffs up to an optimum level of 0.78 nest sites per km^2 (2 per square mile)."

(c) Compensatory relationships. Compensatory relationships exist when a variable with marginal or low value is offset (or compensated for) by the high suitability of other variables. For example:

"The food value for red-tailed hawks in grasslands is related to the percent cover of the herbaceous canopy and the height of the herbaceous canopy between 8 and 46 cm in height."

(d) Spatial relationships. When a species' life requisite resources are found in two or more cover types, spatial relationships are required to complete the habitat model. Cover types are used to define spatial relationships between life requisites (Figure 3-11). The spatial relationships

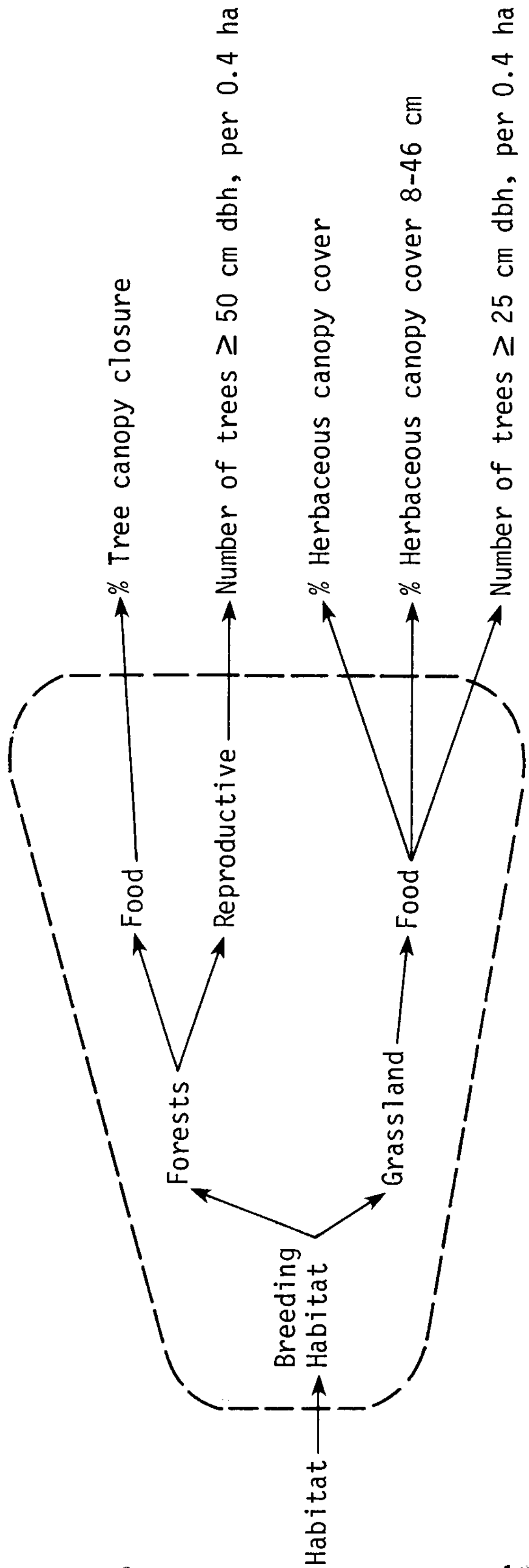

Figure 3-11. The spatial relationships in the red-tailed hawk model.

are built around two variables: (1) distances between cover types (or life requisites); and (2) the relative percent of the habitat area made up of each cover type. The distance relationship is based upon the assumption that there is some minimum linear distance within which all of the species' life requisite resources should be found in order to have optimally suitable habitat. It also is assumed that a maximum distance exists beyond which the habitat is no longer suitable for the species. However, an estimate of the minimum and maximum distance may not be available. Home range extremes reported in the literature can provide these estimates; the desired measure of home range is the major axis (largest length of a home range). Some conversion to linear distance must be made if the reported values are in terms of area. As an initial estimate of the major axis, use the diameter of a circular-shaped home range of equal size. The distance relationship can be expressed as follows:

> "Optimum red-tailed hawk habitat is composed of food-producing areas and areas which provide reproductive habitat which, on the average, are located within 1.2 kilometers of each other. Food and reproductive areas separated by more than 3.6 km are not suitable habitat."

The second spatial variable, percent of the study area made up of each cover type, must be compared to a perceived optimum percentage in order to compute habitat suitability. The optimum percentage defines the relative amount of an area required to provide each life requisite in order to have the best habitat. It may differ for each life requisite resource. This relationship can be expressed verbally for the red-tailed hawk as:

> "Optimum red-tailed hawk habitat is composed of at least 70% optimum food producing areas and at least 15% optimum cover-reproductive areas."

Finally, the two spatial relationships can be combined into one statement:

> "Optimum red-tailed hawk habitat is composed of at least 70% optimum food-producing areas (i.e., grasslands and forestlands) and at least 15% cover and reproductive habitat (i.e., forestlands) which are located within 1.2 km of each other. Food and reproductive areas separated by more than 3.6 km are not suitable habitat."

Table 3-2 is an example word model for the red-tailed hawk. This model was constructed using life history information contained in Appendix B. The variables were identified with the tree diagrams used in 103 ESM 3.2 and are summarized in Figure 3-7.

B. Mechanistic models. In the previous section on word models, word statements were made concerning each variable and the relationship between variables. If these word statements are expressed clearly, they can be translated into mathematical expressions. The advantage of a mathematical expression is the ease of interpretation for many measurements of the variables. This section describes how to convert a word model into a mechanistic model represented by simple mathematical equations.

This progression of defining relationships involves the same two processes that were discussed earlier: (1) the determination of a suitability index for each variable; and (2) the aggregation of suitability indices into a component suitability index.

(1) Describe the suitability of measurable variables. The suitability of a variable is described with a suitability index graph which displays the relationship between the variables and the index of suitability (Figure 3-12).

The horizontal axis of a suitability index graph is scaled to various measurements of the variable. The upper and lower limits of the variable can be defined as either the extreme possible measurements (e.g., 0 and 100 for a percent variable) or measures of the variable beyond which the suitability no longer changes. The vertical axis is bounded below by 0 (no suitability) and above by 1.0 (optimum suitability). "Suitability" is a term that by itself has no specific meaning since one cannot go out and directly measure a suitability level corresponding to a particular variable. However, in constructing this kind of graph an assumption is made that some observation (e.g., survival, standing crop, production, or relative abundance) that is indicative of habitat suitability can be related to the variable. The relationship between habitat suitability and the variable displayed on the graph is assumed independent of other variables which also can affect habitat suitability.

Two basic kinds of suitability graphs can be constructed. One is a continuous curve like that in Figure 3-12. In other circumstances, "measurements" of the variable may be more easily

Table 3-2. Example word model for the red-tailed hawk.

OVERALL HABITAT SUITABILITY

Red-tail breeding habitat is composed of a mixture of feeding areas (i.e., grassland and forests) and reproductive areas (i.e., forests) within a specified distance of each other.

(a) Optimum habitat is 70% optimum feeding areas and 15% optimum cover-reproductive areas on the average within 1.2 km of each other.

(b) Medium suitability habitat occurs when feeding areas occur over 35% of the area, nesting sites occur over 7% of the area or feeding and reproductive habitat is, on the average, separated by 2.4 km.

(c) Marginal suitability habitat occurs when food or cover-reproductive suitability is marginal or when food and cover-reproductive areas are separated, on the average, by more than 3.6 km.

FOREST SUITABILITY

The suitability for food is related to the presence of small mammals and hunting success, both of which are inferred from vegetation structure.

(a) Optimum food conditions cannot occur in forests.

(b) Medium suitability food conditions occur when percent canopy closure of overstory trees is less than 75%.

(c) Marginal habitat occurs when percent canopy closure approaches 100%.

The suitability of forests as cover-reproductive habitat is related to the availability of suitable nest trees.

(a) Optimum reproductive habitat occurs when the number of trees > 50 cm dbh equals or exceeds 25 per hectare (10 per acre).

(b) Medium suitability habitat occurs when the number of > 50 cm dbh trees is approximately 12.5 per hectare (5 per acre).

(c) Marginal suitability habitat occurs when there are no trees or trees are smaller than 50 cm dbh.

GRASSLAND SUITABILITY

Food value is inferred from vegetation structure:

(a) Optimum food suitability occurs when percent herbaceous canopy cover equals or exceeds 65% and at least 50% of herbaceous vegetation is between 8 and 46 cm in height, and 8 or more trees ≥ 25 cm dbh are present per hectare (3 per acre).

(b) Medium food suitability occurs when percent herbaceous canopy closure is 30% or when 25% of the herbaceous vegetation is between 8 and 46 cm in height, and when less than 8 trees ≥ 25 cm dbh are present per hectare.

(c) Marginal food suitability occurs when percent herbaceous canopy cover approaches zero or when none of the herbaceous vegetation is between 8 and 46 cm in height.

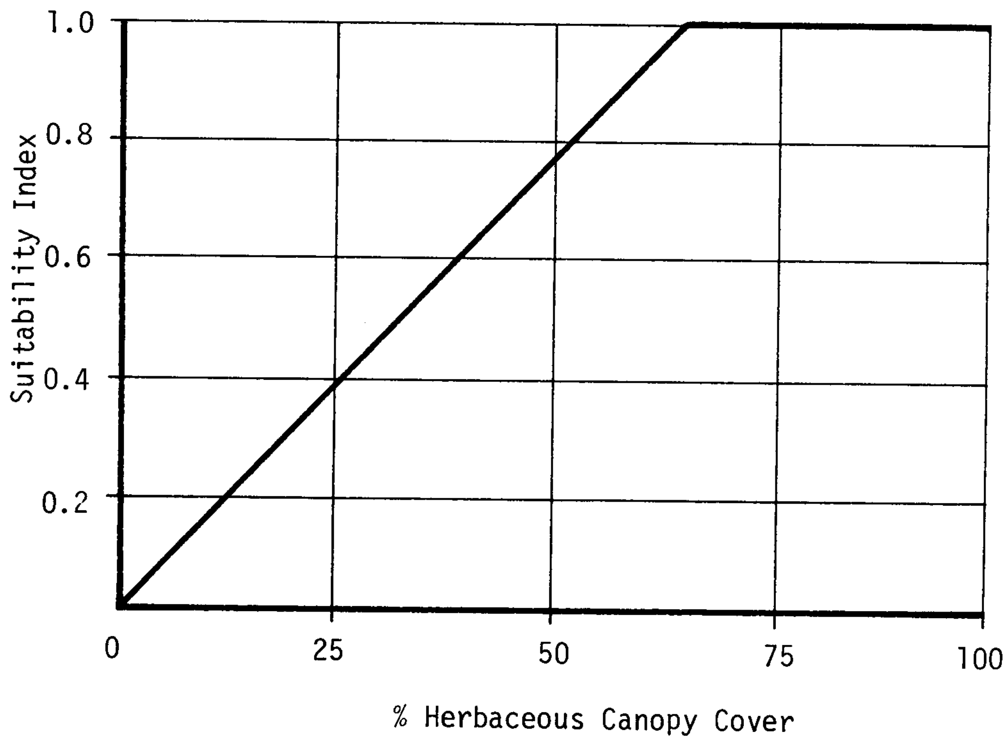

Figure 3-12. Suitability index graph for percent herbaceous canopy cover for the red-tailed hawk.

described in classes or categories. For example, the measure of the variable "availability of grain" could be categorical (abundant, moderate, or scarce). The suitability graph constructed for categorical variables is a histogram (Figure 3-13).

At least three methods may be used to construct suitability index graphs:

a. Method 1. Plot variable measurements against species' response. A suitability index graph can be constructed by plotting specific habitat variable measurements against an observed measure of abundance, such as standing crop. A suitability score of 1.0 is assigned to the range of variable measurements corresponding to the maximum observed abundance. Other measures of the variable are assigned a suitability score equal to the observed abundance at that measured value of the variable divided by the maximum abundance. A limitation inherent to this method of graph construction is the frequent need to base the graph upon several independent studies conducted with different experimental conditions. If that is the case, there is no adequate method to combine this information except by subjective judgment.

b. Method 2. Base suitability index curves on general statements. Suitability graphs can be based upon general statements from the literature. For example, a suitability graph may be based upon integration of a set of statements such as: "The species prefers to nest in the tree canopy"; "Nest sites frequently occur in trees between 25 and 35 feet high"; and "Nest sites are usually found in trees above 15 feet in height." An example graph, constructed from these statements, is shown in Figure 3-14.

c. Method 3. Consult a species authority. "Expert" opinion can be used to define a suitability graph. However, the recommendations of species' authorities can be highly variable and may not be comparable.

(2) Use of the index graph to obtain a Suitability Index score. Suitability Index scores are obtained by comparing existing or predicted conditions in the study area with the relationship depicted by the suitability curve. Scores are interpolated directly from the Suitability Index graph. For example, Figure 3-15 depicts the relationship between percent canopy cover and habitat suitability; a measured 25% canopy cover would

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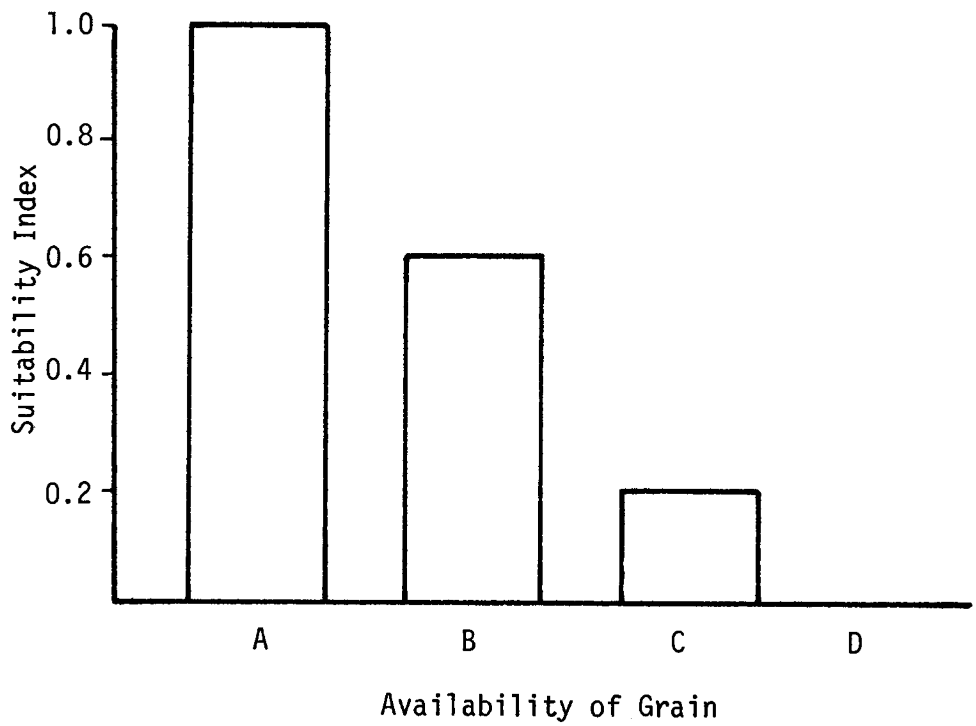

Figure 3-13. Example of a suitability histogram.

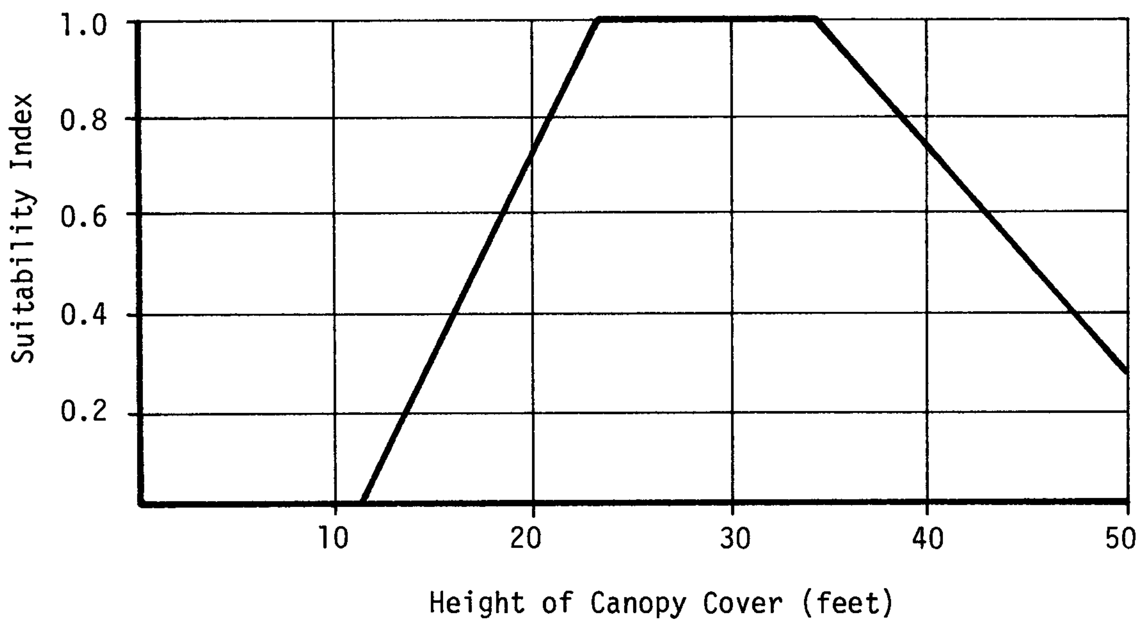

Figure 3-14. Example of a suitability index graph constructed from general statements about a species' habitat preferences.

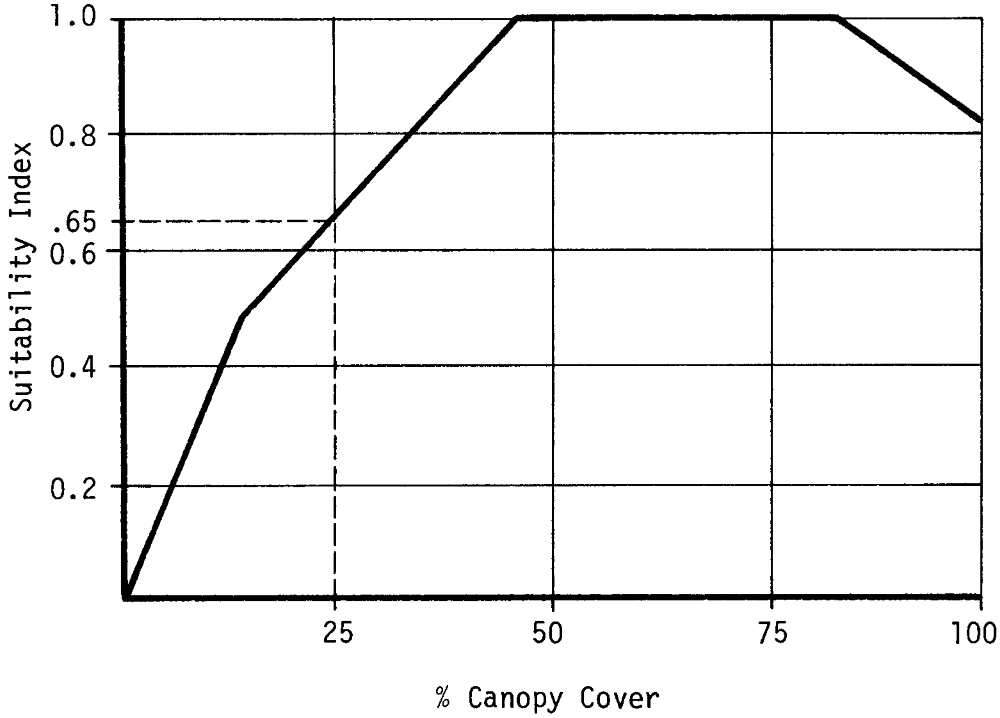

Figure 3-15. Deriving a suitability index for a variable.

receive a suitability index score of 0.65. This method utilizes a precise point relationship for each measurement of the variable. In many instances, the implied precision of this relationship will be greater than the biological data from which the suitability graph was constructed. Therefore, it is important to remember that a suitability graph does not increase the "real" biological precision of a relationship.

(3) Describe relationships between variables. After an index relationship for each variable has been defined, it must be aggregated with others into an index value for the next higher level component in the model. The rules described herein for aggregating indices are the same as those described in the section on word models (103 ESM 3.3A).

(a) Limiting factor method. This type of relationship exists when the variable with the lowest suitability overrides other variables in terms of limiting factor relationships setting the suitability index equal to the lowest variable index as follows:

$$CI = \text{minimum}\ (I_1,\ I_2,\ \ldots\ I_n) \qquad (9)$$

where: CI = component index;

n = the number of variables; and

I_i = the suitability index score of variable i.

This expression allows one variable to be an absolute limiting factor but may be an oversimplification of a limiting factor situation.

An example of this relationship is used to determine the overall habitat suitability using spatial relationships for the red-tailed hawk (Appendix C).

(b) Cumulative relationships. Cumulative relationships occur when a threshold level exists which can be met by any one of several variables or a combination of variables. For example, the optimum density of 0.78 potential nest sites per square km for red-tailed hawks might be provided by trees, cliffs, or both. (This does not apply to the red-tailed hawk model in Appendix B.) For cumulative relationships the index score may not go above 1.0 even though the density of total nest sites exceeds 0.78 per square km. The following mathematical relationship states this condition:

$$\text{score} = \sum_{i=1}^{n} I_i = (I_1 + I_2 + I_3 \cdots + I_n) \text{ if this sum} < 1.0 \quad (10)$$

$$= 1.0 \quad \text{if this sum} \geq 1.0$$

(c) Compensatory relationships. This type of relationship exists when a variable with marginal or low suitability is offset by the high suitability of other variables. A simple mathematical function that describes this relationship is the mean or average value of the individual suitability scores. There are two methods for obtaining an average value. The first method, the arithmetic mean, is expressed as follows:

$$CI = \sum_{i=1}^{n} I_i/n = \frac{(I_1 + I_2 + I_3 \ldots + I_n)}{n} \quad (11)$$

The second method, the geometric mean, is expressed as follows:

$$CI = (I_1 \cdot I_2 \cdot I_3 \cdot \ldots \cdot I_n)^{1/n} \quad (12)$$

where: CI = component index;

n = the number of variables; and

I_i = the suitability index score of variable i.

The following is an example of a compensating relationship for red-tailed hawk food in grassland:

$$\text{Food (Grassland)} = (I_1 \times I_2 \times I_3)^{1/3} \qquad (13)$$

where:

I_1 = Index of percent herbaceous canopy cover.

I_2 = Index of percent herbaceous canopy between 8 and 46 cm tall.

I_3 = Index of number of trees $\geq$ 25 cm (10 in) dbh per 0.4 ha (1.0 acres).

The geometric mean typically produces a smaller score than the arithmetic mean because it is influenced more by low values for one of the variables. For example, when the suitability index scores of variables V_1 and V_2 equals 0.8 and 0.2, respectively, the geometric mean will provide an answer of 0.40 and the arithmetic mean an answer of 0.50. Therefore, one might choose to use the geometric mean when the compensatory relationship is perceived to be weak.

Often when the suitability of any variable is zero, regardless of compensating mechanisms, the CI score should be zero. For example, if both small mammals and birds are required food sources for red-tailed hawks, the suitability value for food should be 0 if the suitability of either food source is 0. The geometric mean will give a score of zero in these cases, whereas the arithmetic mean will not behave this way unless accompanied by the following specification:

$$CI = 0 \text{ if a specified } I_i = 0; \qquad (14)$$

$$\text{otherwise } CI = \sum_{i=1}^{n} SI_i/n = \frac{(I_1 + I_2 + I_3 \cdots I_n)}{n}$$

Averaging functions tend to become insensitive to extremely low or high values in situations where four or more variables are used.

The preceding aggregation techniques assign equal weight to each variable. However, judgement may indicate that the variables are not equal in their significance to habitat suitability. For example, the percent of herbaceous canopy cover may be twice as important as the height of herbaceous vegetation for indicating red-tailed hawk food availability in grasslands. Relative importance of the variables can be considered with the two averaging functions described above by use of a <u>weighted mean</u>. For the arithmetic mean, the suitability index of each variable is multiplied by its weight (W_i) as described in the following equation:

$$CI = \sum_{i=1}^{n} (W_i \cdot I_i) / \sum_{i=1}^{n} w_i$$

$$= \frac{(W_1 I_1 + W_2 I_2 \ldots . + W_n I_n)}{W_1 + W_2 \ldots + W_n} \qquad (15)$$

where: CI = component index;

n = the number of variables;

SI_i = the suitability index score of variable i; and

w_i = the weight of variable i.

For the geometric mean, each suitability index is raised to the power of its weight as described by the equation:

$$CI = (I_1^{W_1} \cdot I_2^{W_2} \ldots I_n^{W_n})^{1/\Sigma W_i} \qquad (16)$$

where: CI = component index;

n = the number of variables;

SI_i = the suitability index score of variable i; and

w_i = the weight of variable i.

An example of the weighted geometric mean is the following equation for red-tailed hawk food value (Appendix B):

$$\text{Reproduction} = (V_1^2 \times V_2 \times V_3)^{1/4} \quad (17)$$

where: V_1 = percent herbaceous canopy cover;

V_2 = percent of herbaceous vegetation that is 8 to 46 cm tall; and

V_3 = number of trees $\geq$ 25 dbh per 0.4 ha.

The method of weighting should be well documented when weights are established for a variable. One frequently used method of establishing importance weights is by consensus of experts (Odum et al. 1976).

(d) Spatial relationships. The HSI aggregation technique must consider interspersion variables if the habitat model for an evaluation species contains two or more cover types. The suggested technique for incorporating interspersion variables was described in the section on word models (103 ESM 3.3A). The two interspersion variables are: (1) distances between cover types; and (2) percent of the study area composed of each cover type.

The relationship of the distance variable to habitat suitability is defined by a suitability index graph (Figure 3-16). This index graph indicates that optimum habitat, from a spatial perspective, will occur when all life requisites are found within a minimum distance (Hmin) of each other. If one or more life requisites are separated from the others by more than some maximum distance (Hmax), the suitability would be 0.0. If the spatial separation of life requisites is more than the minimum but

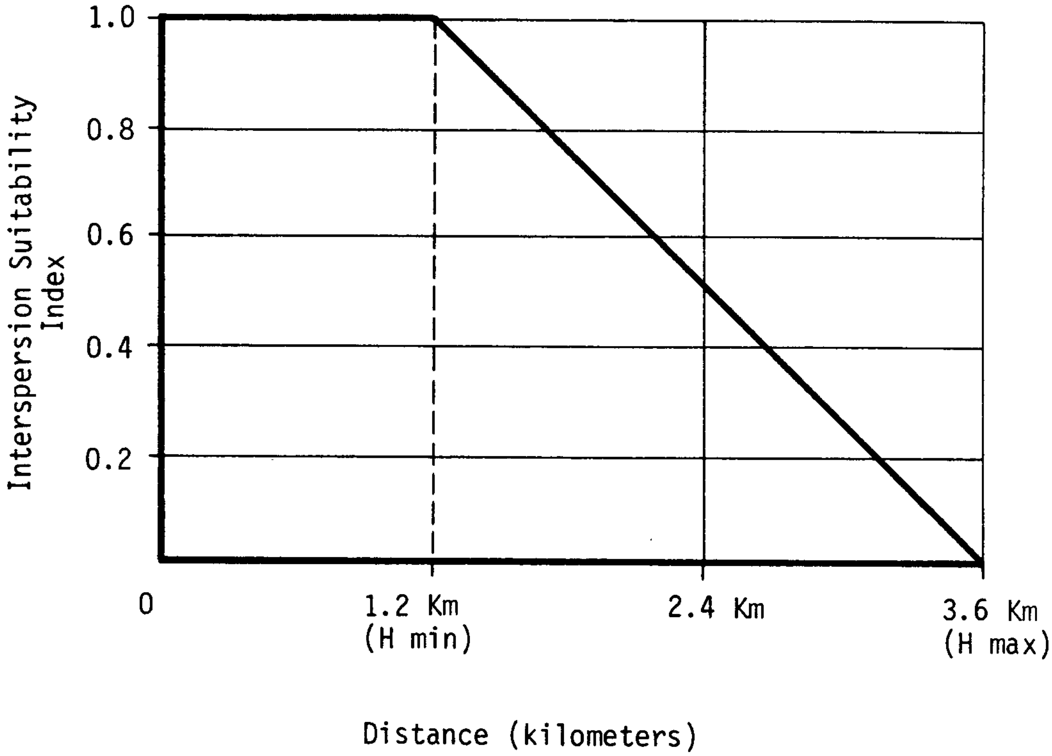

Figure 3-16. Interspersion suitability index graph for the red-tailed hawk.

less than the maximum distance, suitability will be between 0.0 and 1.0 (Figure 3-16). The minimum and maximum distances may be estimated using extremes of home range as reported in the literature.

The interspersion graph is used to adjust the cover type life requisite values. The suitability of the cover type life requisites are adjusted downward as the distance between life requisites (i.e., requisites within cover types) increases.

The percent of a study area composed of each cover type is used to define the proportion of the study area that provides each life requisite. The cover type percent data are combined to calculate percent of the study area providing each life requisite using the formula:

$$LR\% = \sum_{L=i}^{n} (AREA_i)(SI_i) \quad (18)$$

where: $LR\%$ = percent of the study area supplying the life requisite;

$AREA_i$ = the surface area of cover type i;

SI_i = the suitability index for the specified life requisite in cover type i (modified by interspersion graph); and

n = the number of cover types that provide the life requisite.

For each life requisite, the resultant from Formula (18) is compared to an optimum percentage to determine the overall life requisite suitability index. The data in Table 3-3 specify the optimum composition of red-tailed hawk habitat in terms of the percent of the habitat that should supply food, cover, and reproductive needs.

Table 3-3. Composition of study area life requisites required for optimum red-tailed hawk habitat.

Life Requisite	Optimum Percent of Area Needed to Meet Life Requisite Needs
Food	70%
Cover-reproductive	15%

Final determination of habitat suitability is made using the composition parameters. The closer a habitat approaches the optimum composition figures, the higher the suitability will be. For example, a habitat may provide all life requisite resources within specified distances of each other, but food may be located in small plots of low quality. If the size of the plots and the quality of the food are increased, the habitat suitability will increase up to the point where food resources are not limiting and are in balance with other life requisite needs.

An example of a model constructed by this approach for the red-tailed hawk is given in Appendix B, and an example application of distance and composition figures in this habitat model is provided in Appendix C.

C. Pattern recognition models. Pattern recognition models are similar to the previous word model developed for the red-tailed hawk. However, in pattern recognition models, the HSI changes depending upon the pattern of answers for all questions in the models. For example, each of the four questions in Table 3-4 has two possible answers: "Yes" or "No". A set of answers for each situation can be displayed as a distinct pattern (circles in Table 3-4), and each pattern is assigned an HSI. The HSI for each pattern of answers is assigned by expert opinion, based upon information from the literature,

Table 3-4. Graphical display of a pattern recognition model for two habitat conditions.

Question	Condition A		Condition B	
1	(Yes)	No	Yes	(No)
2	Yes	(No)	(Yes)	No
3	(Yes)	No	(Yes)	No
4	(Yes)	No	(Yes)	No

or is assigned by some other method. For example, food (small mammals) in grasslands for the red-tailed hawk could be evaluated by a pattern recognition model as follows. Two variables, percent herbaceous canopy cover and percent of herbaceous canopy between 8 and 46 cm tall, can be divided into two categories each (Table 3-5). Four possible answer patterns can be identified and a food value determined for each. Table 3-6 displays the food value for each answer pattern and documents the reason for the established value.

Variables for pattern recognition models can be defined such that they are easy to measure from aerial photographs or reconnaissance flights over a study area. Thus, these simple models are useful in early stages of project planning.

Pattern recognition models with a large number of variables or a large number of categories for each variable, or both, are more difficult to build and apply. For example, a pattern recognition model with just four questions and three categories has 81 possible answer patterns (3^4). A Suitability Index must be established and documentation provided for each pattern. Adding one additional question with 3 categories increases the number of possible patterns to 243 (3^5); however, it may not be necessary to document all possible patterns.

Table 3-5. Pattern recognition model to evalute red-tailed hawk food in grasslands.

Variable 1	Variable 2
1. Percent herbaceous canopy cover:	2. Percent of herbaceous canopy between 8 and 46 cm tall:
A. Less than (or =) 65%	A. Less than (or =) 50%
B. Greater than 65%	B. Greater than 50%

Table 3-6. Answers for pattern recognition model for red-tailed hawk food in grasslands.

Pattern Number	Food Suitability Index	Reason
1. A,A	0.2	Assumed that little food is available because low food supply for small mammals. Also vegetative cover is too thick (where it does exist) for capturing prey.
2. A,B	0.3	Little food available. However, what is available is easier to catch than in situation 1.
3. B,A	0.6	Good supply of food, yet difficult to capture.
4. B,B	1.0	Good food supply which is easy to capture.