Habitat Suitability Index Models for Masked Bobwhite

Final Report

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Background and Introduction

Since the initial discovery of masked bobwhite in 1864 and subsequent description in 1884, the species has had a tenuous history. Masked bobwhite were thought to be extirpated in southern Arizona by 1900 and believed extinct in Sonora, Mexico by 1950. Three isolated, wild populations were subsequently re-discovered in Sonora between 1964 and 1992, two of which are thought to have since disappeared. During the past 10 years, only two small populations were known to exist in the wild, one on the Buenos Aires National Wildlife Refuge (BANWR) and one on several private ranches in north-central Sonora, Mexico. Numbers of birds in these two areas have declined in recent years and no birds were detected in either location during the 2009 standardized survey effort (although BANWR staff reported several incidental detections of birds in 2009).

Captive birds have been released repeatedly over the last four decades, but these recovery efforts have had little or no lasting success. The sole population in the U.S. (at BANWR) required annual supplementation of captive-reared individuals. The sole wild population in Mexico: 1) is small, and may already be extirpated; 2) is adversely affected by livestock grazing and planting of buffelgrass (*Pennisetum ciliare*); and 3) will likely be extirpated soon without more intensive management efforts. The Masked Bobwhite Recovery Plan (U.S. Fish and Wildlife Service 1995) suggests a habitat suitability analysis to guide habitat management and bobwhite reintroduction efforts in the U.S. and Mexico. The success of masked bobwhite recovery may depend upon synthesizing masked bobwhite habitat requirements, identifying areas with remaining habitat, and managing existing habitat to improve habitat suitability. Unfortunately, traditional methods of developing and testing a habitat suitability model are not feasible because no wild populations are known to exist. Moreover, making inferences regarding habitat suitability from birds occupying sub-optimal habitat could produce biased conclusions and ineffective management actions. We sought to overcome these obstacles by using both published literature and expert opinion to develop a suite of habitat suitability index models for Masked Bobwhite.

Habitat suitability index (HSI) models were introduced by the Biological Services Division of the U.S. Fish and Wildlife Service in 1981 to better evaluate fish and wildlife habitat needs by combining expert opinion and published literature to clearly define the suitability of areas based on important habitat components (Shamberger and Krohn 1982). The method was developed in response to the *Habitat Evaluation Procedures* (U.S. Fish and Wildlife Service 1980), which was a technique for evaluating changes to wildlife habitat resulting from land and water use changes. HSI models are divided into three components: 1) written description of habitat relationships, 2) graphical representation of those relationships, and 3) mathematical representation of the relationships. Typical HSI models combine both published literature and the opinions of multiple species experts into a single model to consolidate information from multiple sources into a single, consensus document and model. The original intention of HSI models was to create testable hypotheses of species-habitat relationships (Shamberger and Krohn 1982) rather than proven cause-and-effect relationships.

Development of a single HSI model for masked bobwhite would be very difficult and may unnecessarily homogenize some important disagreement over the most important components of optimal habitat for masked bobwhite. Limited published literature exists on the masked bobwhite and much of this research was conducted either on birds in Mexico during a period of severe population decline, or on captive-bred birds in the U.S. that may or may not exhibit the same habitat associations as wild birds. For these reasons, habitat relationships in the published literature should be interpreted with caution. Likewise, recognized experts on masked bobwhite differ somewhat in their opinions regarding the most suitable habitat features for masked bobwhite. Rather than attempting to incorporate disparate opinions into a single consensus model, we developed a suite of habitat suitability models: one that reflects information in the published literature and one for each masked bobwhite expert. The individual models can then be used as alternative hypotheses where they differ and management guidelines where they agree. Moreover, we used lower confidence limits (across all candidate models) as a conservative estimate of overall habitat suitability for a given area, which provides a consensus estimate of habitat suitability taking into account the disagreement among species experts.

Project Objectives

Our three primary goals for this project were: 1) Summarize/synthesize important habitat features for masked bobwhite; 2) Quantify the explicit relationship between these important habitat features and habitat suitability for masked bobwhite; and 3) Translate the various bivariate relationships between habitat features and habitat suitability into a suite of mathematical habitat suitability models.

Methods

Objective 1. Summarize/synthesis important habitat features for masked bobwhite

With the help of the Masked Bobwhite Recovery Team, we identified 12 masked bobwhite experts for the creation of individual HSI models. We contacted each expert and asked them to meet with us for face-to-face interviews for the purpose of recording their knowledge of masked bobwhite habitat suitability. Three of the 12 species experts that we contacted did not respond to multiple requests for an interview (G. Camou, E. Gomez, and J.

Levy). We used the following questions to aid in collecting information about masked bobwhite habitat from the remaining 9 experts:

- What has prevented masked bobwhite from persisting or recovering?
- What are the most important habitat characteristics for masked bobwhite?
- How does season (time of year) affect these variables and their relative importance?

Objective 2. Quantify the explicit relationship between these important habitat features and habitat suitability for masked bobwhite

We initially selected 5 habitat variables which were also mentioned in the published literature. We sought to describe the quantitative relationship between each of these 5 variables and habitat suitability for masked bobwhite. The 5 initial habitat variables were: 1) Percent overhead cover of woody vegetation (brush and shrub), 2) Percent basal cover of bare ground, 3) Height of grass clumps used for nesting, 4) Percent overhead cover of herbaceous vegetation (grass and forbs), and 5) Visual obstruction (at ground level). We used means (and ranges) of habitat variables identified during interviews with species experts and from the published literature to produce a suite of potential habitat suitability relationships for each habitat variable. In cases where a species expert or published article provided a mean but no range, we produced three graphs with varying degrees of variance: high, medium, and low. For example, graphs with high variance would indicate suitability for masked bobwhite over a broad range of conditions. Conversely, graphs with low variance would indicate a situation where only a narrow range of habitat conditions were suitable for masked bobwhite. In cases where a species expert or published article provided a range but no mean, we created graphs with varying levels of kurtosis (skew) to create various means (low, centered, and high) within a given range. The number of graphs produced for each variable reflects either the degree of uncertainty about the relationship, or the diversity of initial opinions among species experts, or both. Suitability relationships for the 5 initial habitat variables, along with their probability density functions are presented in Appendix A. Unfortunately, the relationships produced from this initial effort were not well received by several species experts because they thought that the relationships represented were too general (i.e., they did not take into account season or geographic location). In response to input from species experts from this initial attempt at graphical representation of habitat relationships, we employed a slightly different technique (described below under Objective 3).

Objective 3. Translate the various bivariate relationships between habitat features and habitat suitability into a suite of mathematical habitat suitability models.

Only 6 of the 9 species experts agreed to assist with this second phase of the project. Two of the 3 species experts (Kuvleski, Dobrott) that declined said that they would have no additional information beyond what was already available in the published literature or by other participating experts, and the third expert (Brown) took issue with our methodology and decided not to participate further. We incorporated feedback from the species experts and modified our method for creating HSI models. Instead of using pre-determined probability distributions developed from literature and expert interviews for inclusion in individual HSI models, we asked experts to manually draw hypothetical suitability relationships between each habitat variable and masked bobwhite habitat suitability. We then developed mathematical probability distributions which closely replicated each expert's drawing. We used this method to complete HSI models for each of 6 species experts. We sent drafts of the probability distributions and the HSI model back to each corresponding expert for their verification. We received additional feedback on the draft HSI model from all 6 species experts and incorporated their suggested changes. We also developed a HSI model based solely on habitat relationships described in the published literature. We produced 2 HSI models each (one for Mexico and one for the U.S.) for John Goodwin and the literature because both sources suggested substantial differences in habitat affinities. Hence, we produced a total of 9 separate HSI models.

Additional Work

We made attempts to incorporate our work with the broader work of the U.S. Fish and Wildlife Service. We initially met with Dr. Steven Sesnie, a spatial ecologist for the U.S. Fish and Wildlife Service, on 25 May 2012 to discuss how we could assist his work on spatial models for masked bobwhite habitat. We met again (over the web) with Dr. Sesnie and Dr. Lacrecia Johnson (U.S. Fish and Wildlife Service Zone Biologist for the Sonoran and Chihuahuan Deserts) on 12 October, 2012. Drs. Sesnie and Johnson are currently collecting habitat data on a stratified random sample of 50x20m plots on the Buenos Aires National Wildlife Refuge. They are also submitting a grant application to the Joint Fire Sciences Program to fund a study evaluating the use of fire for managing habitat for masked bobwhites. They were interested in what our habitat models suggested as the most important habitat components for masked bobwhite. We discussed our draft results and we provided all 7 complete masked bobwhite HSI models for them to reference while collecting habitat information on the refuge (Appendix B). We also discussed how suitability scores based on each HSI model for each plot could then be used to train a remote sensing model for use in other portions of the species historic range, such as northern Mexico.

Model Interpretation

Quantifying the uncertainty associated with the suite of 7 HSI models that we developed is important for land managers who wish to improve masked bobwhite habitat or find new potential release sites. Multiple sources of uncertainty are associated with each HSI model, including uncertainty related to:

1. Variable selection
2. Suitability functions
3. The structure of the model
    a. Relationships among variables
    b. Importance of variables relative to one another
    c. Latent variables (Food, Reproduction, etc.)
4. Measurement error of model inputs

We focused our efforts on the quantification of uncertainty of the suitability functions (#2 above) and uncertainty in the structure of the model (#3 above). Understanding the degree of uncertainty in these areas will help land managers make decisions about habitat management, and will also identify the habitat variables which contain the greatest degree of uncertainty (and hence deserve additional research/discussion). Understanding the greatest sources of uncertainty will be important for directing future research efforts to further our understanding of the species-habitat relationships for masked bobwhites. Understanding uncertainty will also be important for identifying a suite of alternative release sites that incorporate the habitat conditions that span the range of uncertainty (to learn from the release and to ensure that released masked bobwhite are more likely to find suitable habitat conditions within the release area).

Uncertainty of Suitability Relationships

Past efforts to quantify uncertainty in expert opinions typically require the expert to explicitly specify their confidence. Unfortunately, an expert's confidence in their own knowledge is likely to be a function of many factors, only one of which relates to the precision of their knowledge about the species-habitat requirements. Hence, we used the complete set of expert opinions to quantify uncertainty in the species-habitat models. We assumed that the "true" relationship between each habitat variable and suitability for masked bobwhite is spanned by the variation among our 7 expert opinions (6 species experts plus the literature). Therefore, the degree of uncertainty surrounding any suitability function is defined by the entire set of functions across all species experts. We created graphical representations of this uncertainty for each habitat suitability relationship identified by the 7 expert opinions. The uncertainty represented in these graphs can be measured by integrating over the domain of the relationship to determine the area of each uncertainty estimate. Our method treats each relationship as an exact mapping of a habitat metric to a suitability value. Therefore, the uncertainty estimated in this manner is likely to underestimate the true uncertainty associated with these relationships since there is likely to be uncertainty associated with each individual relationship.

Uncertainty of HSI model structure

We simulated 3 sets of data to quantify the uncertainty associated with the structure of each model. We bypassed the individual suitability relationships for each variable by simulating a single map of HSI values for each variable. We modeled HSI values for each variable as an independent random symmetric beta process with a mean of 0.5 (the choice of 0.5 was arbitrary- we merely had to pick some value to assess uncertainty); let x_j be a measure of a habitat variable at location j,

$$S_i(x_j) = \frac{{x_j}^4(1-x_j)^4}{B(5,5)}, and$$

$$E\left[\sum_{j=1}^{p} S_i(x_j)\right] = 0.5 \; \forall \; S_{i,}$$

where $S_i(x_j)$ is the suitability for variable i at location j and p is the number of pixels in the area modeled. Therefore, if a model were a linear function of the individual suitability scores it should produce a mean suitability score of approximately 0.5 for the area modeled; e.g.

$$E\left[\frac{1}{n}\sum_{i=1}^{n}\sum_{j=1}^{p} S_i(x_j)\right] = 0.5,$$

where *n* is the total number of variables in the HSI model. We then applied this multi-layered map to each individual HSI model. We then calculated the difference in overall habitat suitability assigned to each pixel by each model. We use the mean difference in scores from equivalent suitability relationships as an estimate of the uncertainty associated with the model structure. We then compared this to the mean difference between models for each pixel when models were applied to simulated environmental data to estimate the amount of uncertainty associated with model structure versus the individual suitability functions within each model. We compared the mean suitability from each model to the expected mean suitability to determine important structural elements within each model.

For each of three simulations we also compared overall suitability, variation in suitability and the range of suitability values created by each model. These metrics identify models which have structures that do a good job of discriminating between high- and low-quality habitat. Comparing the mean of the scores to the expected mean score (0.5) for a linear combination of the variables provides information as to whether the models are optimistic (i.e., produce a higher mean score than would be expected) or pessimistic (i.e., produce a lower mean score than would be expected).

Habitat simulation and prediction

We created 3 simulated masked bobwhite habitats and applied each individual HSI model to each of the simulated habitats to aid interpretation of the models. We started by simulating each of 26 different habitat components across an area of 4 ha (40,000 m^2). We used the range of values represented in the set of HSI models as possible values in the simulation. In order to better simulate real-world habitat data where habitat features are typically spatially correlated, we gave each variable a level of autocorrelation between $\rho=0.95$ and $\rho=0.99$. We assigned autocorrelation to pairs of habitat variables that are likely to be correlated in nature (e.g., tree cover is likely to be negatively correlated with grass cover). We then provided the same sets of variables to each HSI model and calculated the HSI value for each of 10,000 4-m^2 pixels within the area. Certain habitat variables (such as percent overhead cover of various habitat components) can be appropriately measured at the pixel level. However, other habitat variables (such as Mary Hunnicutt's structural diversity variable and Roy Tomlinson's tree cover variable) reflect habitat features at larger scales that can't be measured at an individual pixel. For these large-scale variables, we created a buffer around each pixel of appropriate size (e.g., 0.4 ha for Mary Hunnicutt's structural diversity variable) and calculated the suitability of each pixel based on the value returned by the floating buffer. We calculated suitability scores for each individual model, including separate models for Arizona and Mexico for John Goodwin's HSI model and the literature HSI model. We then compared the range of suitability scores, the variability of suitability scores, and the mean suitability score for each model.

Results

Objective 1: Summarize/synthesis important habitat features for masked bobwhite

The 9 experts involved in phase 1 of the project identified 22 separate issues that they suggested affect masked bobwhite recovery. We removed 2 of these issues (breeding problems among the released birds and ability of captive birds to survive in the wild) because they were unrelated (or only very indirectly related) to habitat suitability. The remaining issues are a combination of measurable habitat features (e.g., leguminous shrubs) and ultimate processes (e.g., winter food) that affect habitat selection. We also asked experts to rank each variable in order of importance. The variables and their associated ranks are presented in Table 1. As might be expected, not all experts mentioned (and hence provided ranks for) the same suite of variables. Whenever an expert failed to rank a variable that was mentioned by other experts, we inferred a rank from our discussions with that expert during the interview. We did not include a rank for a particular habitat variable if that variable was not discussed in enough detail by the expert to infer a rank. We summarized the overall importance of each variable (among all 9 experts) by taking an average of the ranks for each variable. We calculated variable weights by taking the inverse of the average rank (Table 2).

Objective 2. Quantify the explicit relationship between important habitat features and habitat suitability for masked bobwhite

We produced 7 HSI models (Appendix B). We also provide documented (annotated) R code that will produce HSI scores from the models for any given area with the input of appropriate raster layers of habitat variables (Appendix C).

Uncertainty of Suitability Relationships

We created uncertainty plots for each habitat-suitability relationship. Figure 1 shows the utility of these graphs for identifying habitat variables with considerable uncertainty. This method allows direct comparison of uncertainty among all habitat-suitability relationships identified by the experts (i.e., it allows us to compare uncertainty among different habitat variables with different units of measurement). Table 3 contains a list of the habitat-suitability uncertainties.

Uncertainty of Model Structures

The functional form (model structure) of each model also influenced the suitability assigned to an area. We plotted each of the HSI models over 3 sets of identical suitability scores for each variable (Figs. 2 – 4). Figure 5 shows the upper and lower limits of the uncertainty associated with model structure for the first simulation. The average range of suitability scores across the three simulations was 0.287. Using this as a measure of uncertainty would create an error of +/- 0.144 for a suitability score. A more conservative measure of uncertainty would be the average maximum range of suitability scores. For the three simulations, the average maximum range of suitability scores was 0.765. Using this measure of uncertainty would create an error of +/- 0.383. The uncertainty associated with the suitability predictions from the simulated environmental data includes both uncertainty associated with the individual habitat variable-suitability relationships as well as the uncertainty associated with model structure. The average range of scores from the three data simulations was 0.571 and the average maximum was 0.840. We determined the proportion of uncertainty due to model structure by comparing these two uncertainties. Using the <u>mean</u> range of suitability scores as the measure of uncertainty, model structure accounted for (0.287/.571)*100 = 50.3% of the total uncertainty. Using the maximum average score as the measure of uncertainty, model structure accounted for (0.765/0.840)*100 = 91.1% of the total uncertainty.

Model functional forms also differed in their ability to discriminate between high- and low-quality habitat. Table 4 lists the mean, minimum, maximum, and variance of the overall suitability scores generated by each model for the three simulations of suitability scores (i.e., these values represent the differences in model structure alone). Models from the literature and John Goodwin were equivalent between Arizona and Mexico after eliminating the individual suitability functions. John Goodwin's model (the functional form) had the highest variance indicating that it can discriminate well between high- and low-quality habitat. Two other models (those produced by Sally Gall and Dan Cohan) also had functional forms that did a good job of discriminating between high- and low-quality habitat. Mary Hunnicutt's model structure had the smallest range of scores and the lowest variance. The expected mean suitability score for a linear model applied to the simulated suitability scores is 0.5. All of the model structures produced mean scores that were substantially lower than this value (0.444 was the highest mean score).

Habitat Simulation and Prediction

The 9 different HSI models (we included 2 models each for John Goodwin and the literature to reflect differences between Mexico and the U.S.) produced different predictions of habitat suitability when projected on the same simulated environmental variables. Figures 6 through 8 represent the HSI scores from the 9 models applied to 3 different computer simulations. The relative HSI scores for each model remained the same for all three simulations indicating that the models are fairly robust to random changes in data input. All 3 simulations were made based on the same parameters and therefore represent variation which would occur randomly between sites of equivalent suitability. Changing the values of these parameters would change which models gave the highest and lowest suitability scores. Therefore, a better metric for comparing models may be to examine the ability of each model to differentiate between high- and low-quality habitat. If a model rates all areas equivalently, it will likely perform poorly at discriminating between high- and low-quality habitat for masked bobwhites and will be of limited use by managers. Table 5 lists the mean, minimum, maximum, and variance of the suitability scores generated by each model for the three habitat simulations. John Goodwin's models for both Mexico and Arizona had the highest variance and range of scores and, therefore, did the best job of discriminating between high- and low-quality habitat. The model developed from the literature for Arizona did the worst job of discriminating areas with differences in habitat quality. Figure 9 shows the upper and lower confidence intervals for overall habitat suitability from the first simulation. In the absence of additional information about which model most closely approximates the truth, the lower confidence limit can be used as a conservative estimate of overall habitat suitability for a given area and can be considered a consensus estimate of habitat suitability.

Discussion

We interviewed 9 masked bobwhite experts and determined the most important habitat characteristics for masked bobwhites. We also developed a suite of habitat suitability models which together summarize and synthesize the best available information regarding the habitat needs of masked bobwhite. Although the 9 models differ substantially in content, each model outlines the specific rationale for the relationships contained in the model, thereby providing a foundation for formulating and testing specific hypotheses about the habitat requirements of masked bobwhites. Climate, leguminous shrubs, thermal refugia, and winter food were the features ranked as most important for masked bobwhite by species experts.

The suite of HSI models we developed will provide a foundation for evaluation and improvement of masked bobwhite habitat. The metrics of uncertainty we quantified will focus research into areas with the greatest need. This will increase the speed with which new information about the relationship between masked bobwhites and their environment is acquired. We also developed tools for habitat evaluation which will allow managers to determine the most limiting habitat feature in a given area and target improvement efforts at these limiting resources.

The HSI models included in this report are either based solely on expert opinion or on limited data collected during population declines of masked bobwhites. Therefore, all of the models should be treated as competing alternative hypotheses and should be tested, if possible, with data on actual masked bobwhite habitat quality measures. However, future tests of these habitat hypotheses may be impossible if additional endemic, stable populations are not located. Several of the habitat suitability functions had relatively low uncertainty. These include the proportion of bare ground, tree and forb cover, and shrub height. We also found consensus on the general relationship between forb and grass diversity and suitability even though the precise number of species differed among masked bobwhite experts. We suggest that these variables are suitable for immediate management action to improve habitat quality in both Arizona and Mexico. However, these variables alone may be insufficient to identify high-quality masked bobwhite habitat. We recommend targeting research efforts to reduce the uncertainty associated with each of the habitat relationships included in the HSI models.

We found that model structure accounted for between 50% and 90% of the total uncertainty depending on the measure of uncertainty used. This suggests that the structure of each model is an important component of each HSI model. This result is not surprising since the model structure identifies how all of the habitat components fit together to produce high-quality habitat for masked bobwhites. Therefore, model structure should clearly be included when evaluating each HSI model as a competing alternative hypothesis. The predicted mean habitat suitability scores from each model were substantially lower than the expected score of 0.5. This is due to a common feature in the models; the overall suitability score for each model is the minimum score from each of the habitat requisites (e.g. food, cover, and thermal protection) identified in the model. All of the authors included this structure in their models indicating a consensus that habitat suitability for masked bobwhites is greatly influenced by the most-limiting habitat component. We recommend managers capitalize on this feature and use these models to identify the limiting features of any potential reintroduction area and target management efforts to improve these limiting features (see below).

The models developed from the literature, Dave Ellis' model, Mary Hunnicutt's model, and Roy Tomlinson's model all had relatively low variance. This is likely because they each had suitability functions that were applied over a buffer (i.e. they included a habitat feature that needed to be measured at a larger scale than the individual pixel). This will reduce the variation in HSI scores over a relatively small area (when compared to the size of the buffer) but this effect will diminish as a larger area is modeled. Moreover, the simulated habitat used in this report may or may not reflect realistic habitat features in potential reintroduction areas and the results of model comparisons are sensitive to the habitat conditions in the area(s) where models are applied. However, simulations can help to understand how and why models produce substantially different suitability scores for a given area. For example, Roy Tomlinson's model produced much lower suitability scores than Mary Hunnicutt's model in all three of our data simulations. Roy Tomlinson's model uses the minimum suitability score from either the summer or the winter. A closer evaluation shows that the simulated habitat is more suitable in summer than in the winter (Fig. 10). If accurate, this information could be used to target management activities to improve winter habitat and avoid needlessly improving summer habitat. Figure 11 shows the predicted habitat suitability of a simulated area based on individual habitat components from an HSI model developed from masked bobwhite habitat relationships identified in the literature. Investigating model components in this way can be used to investigate the underlying habitat deficiencies at any level of the model and can therefore provide detailed information to managers about what management actions need to be taken at geographically specific locations to achieve the maximum benefit in terms of habitat suitability. The example in Figure 11 suggests that habitat components related to reproduction are the most limiting characteristics and variables related to food availability are the least limiting. The simulations presented in this report are not based on any real habitat data, and are presented as a demonstration of how these models could be applied. Applying these models to real data from a suite of potential reintroduction sites would provide insights into the features of each area that may warrant modification prior to release.

Additional research into masked bobwhite habitat suitability is needed. Our results should help ensure that future research of habitat suitability of masked bobwhite is as efficient and productive as possible. We recommend using the attached suite of habitat suitability models as competing alternative hypotheses and conducting experiments which can discriminate among them. For example, future releases could be conducted in several areas (each rated as high-quality by some models and not-so-high quality by others) and any differential survival among areas could help identify which models are more likely. We also recommend using the information embedded within each model to infer the most effective management actions. Until additional model validations and revisions are conducted, we recommend using the lower confidence limit of overall suitability scores (Fig. 9) from the suite of HSI models as a conservative estimate of overall habitat suitability.

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	Avian Predators	Winter Food	Invasive Plant spp	Climate	Woodland /Grassland Edges	Thermal Refugia	Brush and Shrub Cover	Vegetation Height (herbaceous)	Leguminous Shrubs	Vegetation Structural Diversity	Arthropod Diversity and Abundance	Bare Ground	Grass Cover	Tree Cover	Mammalian Predators	Herbaceous Species Diversity	Forb Cover	Water
Expert 1	-1													-1	-2			6
Expert 2		1	-2	3					1		4					4		5
Expert 3				1		2	3			5		4	5	2		6	3	
Expert 4	-8	3	-7	6	2		3	9	3			4	1		-8		5	
Expert 5	-4	1			5	3	2			5			6	6	-4		6	
Expert 6		6			4		3			1	6		4	5		2	6	
Expert 7			-1	1	3		5		2	3		4	3	6		1	2	16
Expert 8			-16	1			6		3				5			2	4	16
Expert 9				1														

Table 1. Map of important variables showing degree of similarity in the rank of each variable among 9 masked bobwhite experts. Not all of the 9 species experts ranked each variable (see text). Where no rank was given to a variable, we inferred a rank from discussions with that species expert during the interview. A variable received no rank if it was not discussed in enough detail by an expert to infer a rank. Low numbers imply high importance whereas high numbers imply low importance.

Table 2. Variables listed in order from most important to least important according to consensus among 9 masked bobwhite experts.

Habitat Variable	Rank	$Weight^{-1}$
Climate	1	2.166667
Leguminous Shrubs	2	2.25
Thermal Refugia	3	2.5
Winter Food	4	2.75
Herbaceous Species Diversity	5	3
Woodland /Grassland Edges	6	3.5
Vegetation Structural Diversity	7	3.5
Brush and Shrub Cover	8	3.666667
Bare Ground	9	4
Grass Cover	10	4
Tree Cover	11	4
Avian Predators	12	4.25
Forb Cover	13	4.333333
Mammalian Predators	14	4.5
Arthropod Diversity and Abundance	15	5
Invasive Plant spp	16	6.5
Vegetation Height (herbaceous)	17	9
Water	18	10.75

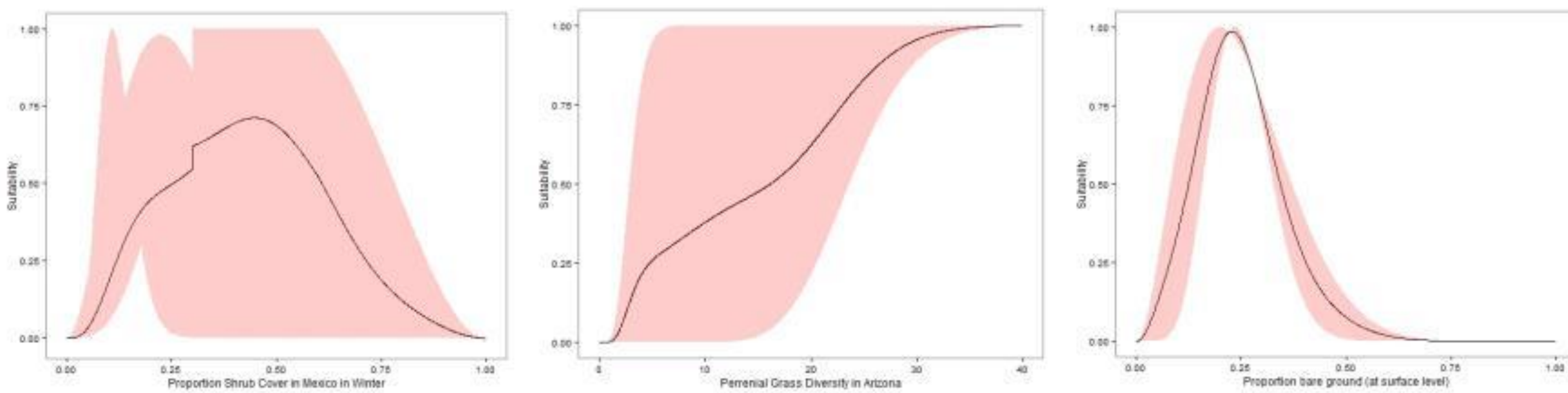


Figure 1. Examples of three habitat-suitability plots with estimates of uncertainty. The black curve represents the mean suitability relationship among all experts and the red band represents the uncertainty associated with the suitability relationship. Uncertainty is measured by the diversity of opinion among all of the species experts. The graph on the left shows a great deal of uncertainty whereas the graph on the right shows only a small amount of uncertainty. The middle graph contains a moderate amount of uncertainty but does contain a consensus on an optimal level of grass diversity.

Table 3. Estimates of uncertainty associated with each relationship between a habitat feature and suitability for masked bobwhite. Estimates are ordered from highest (most uncertainty) to lowest (least uncertainty). Estimates of uncertainty were obtained by calculating the area of the uncertainty bands associated with each habitat-suitability relationship (see Figure 1). Uncertainty estimates are standardized for all variables to control for differences among variables in measurement units and scale.

Habitat Variable	Uncertainty	Habitat Variable	Uncertainty
Forb Cover: AZ, Summer	988.1		
Forb Cover: AZ, Winter	988.1	Proportion of Bare Ground	630.2
Forb Cover: MX, Winter	986.7	Tree Cover: AZ, Uplands, Winter	603.7
Forb Cover: MX, Summer	986.7	Tree Cover: MX, Arroyos, Winter	586.0
Perennial Grass Cover, MX	974.6	Grass Height for Cover	557.6
Annual Grass Cover, MX	974.5	Annual Grass Diversity, MX	550.0
Perennial Grass Cover, AZ	956.9	Annual Grass Diversity, AZ	549.9
Annual Grass Cover, AZ	956.8	Forb Height in the Spring	530.6
Forb Diversity	787.5	Tree Cover: MX, Arroyos, Summer	527.7
Shrub Cover: MX, Summer	681.5	Perennial Grass Diversity, MX	527.3
Shrub Cover: MX, Winter	681.5	Perennial Grass Diversity, AZ	524.9
Forb Height in the Fall	680.6	Tree Cover: MX, Uplands, Summer	523.7
Shrub Cover: AZ, Summer	669.5	Tree Cover: AZ, Arroyos, Summer	522.2
Tree Cover: MX, Uplands, Winter	649.7	Grass Height for Nesting	511.8
Shrub Cover: AZ, Winter	635.0	Tree Cover: AZ, Uplands, Summer	480.9
Tree Cover: AZ, Arroyos, Winter	632.0	Shrub Height	127.2

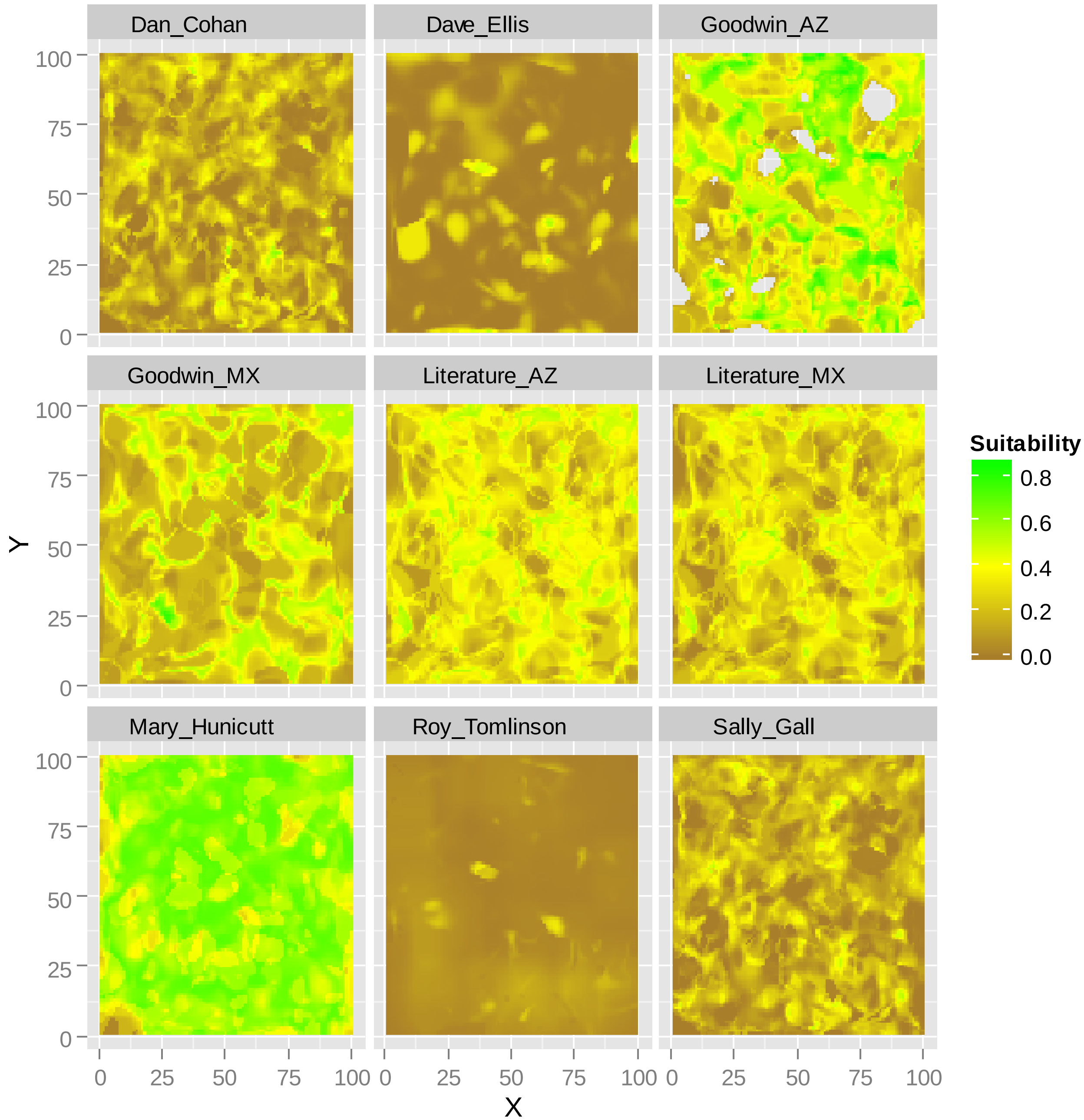


Figure 3. Habitat suitability scores from the 9 HSI models based on the same simulated data. Suitability scores varied substantially among models.

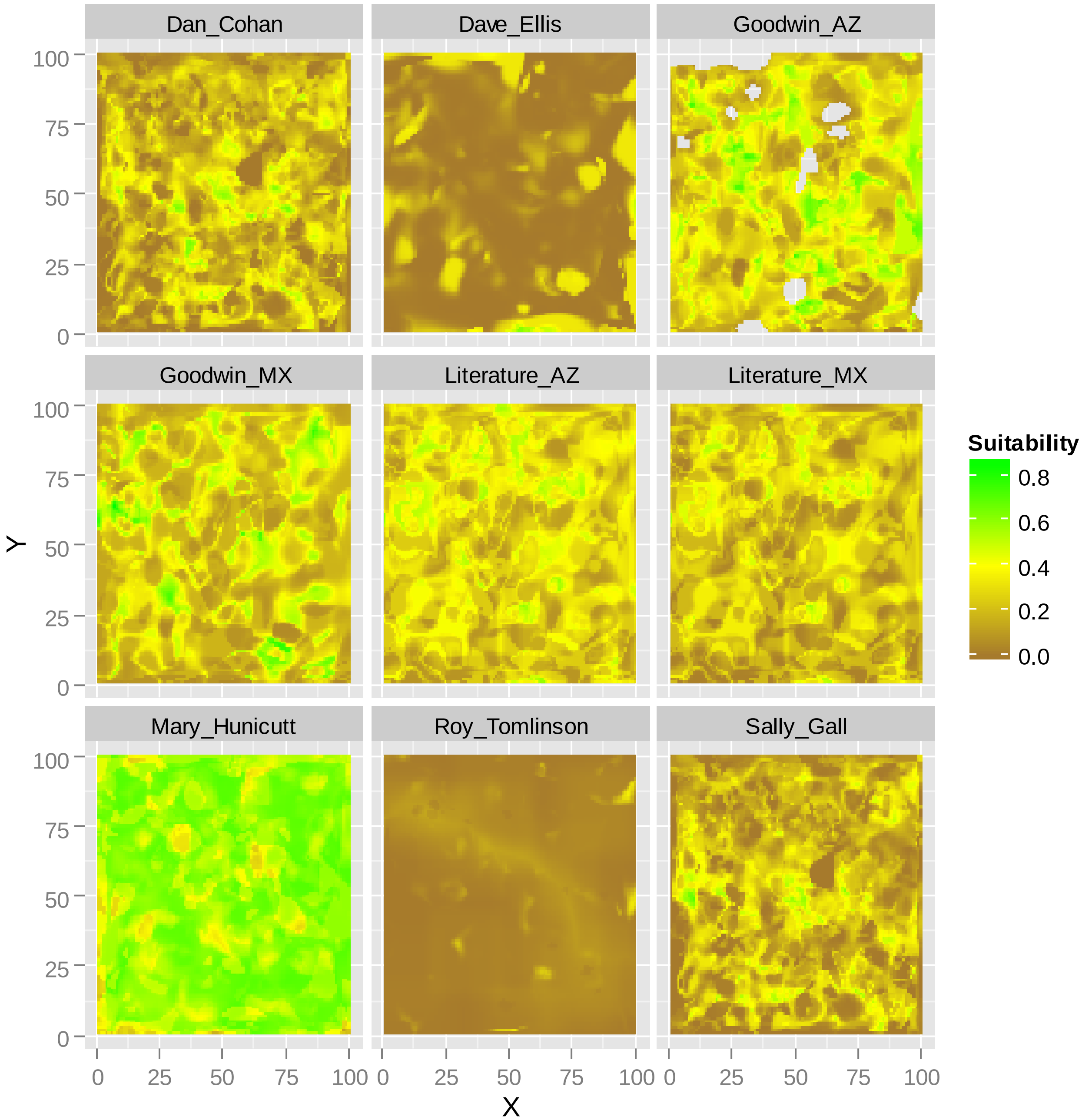


Figure 4. HSI plots from the 2nd data simulation. All HSI maps are generated from the same simulated area. Roy Tomlinson's and Dave Ellis' models had the lowest overall scores whereas Mary Hunnicutt's model had the highest overall score, which is consistent with the other simulations.

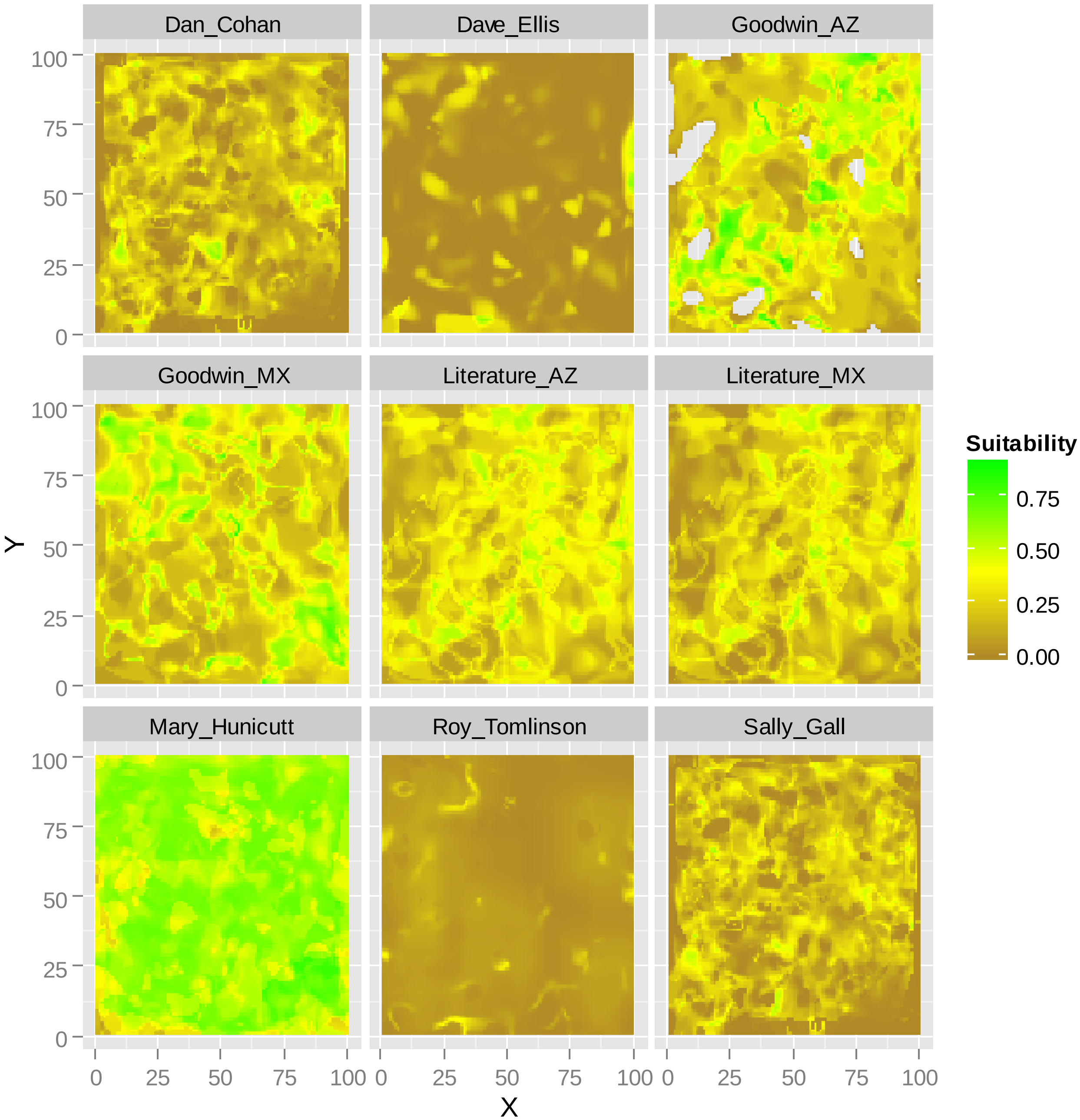


Figure 5. Habitat suitability scores from the third simulation. The pattern in suitability scores was similar among the three different simulations.

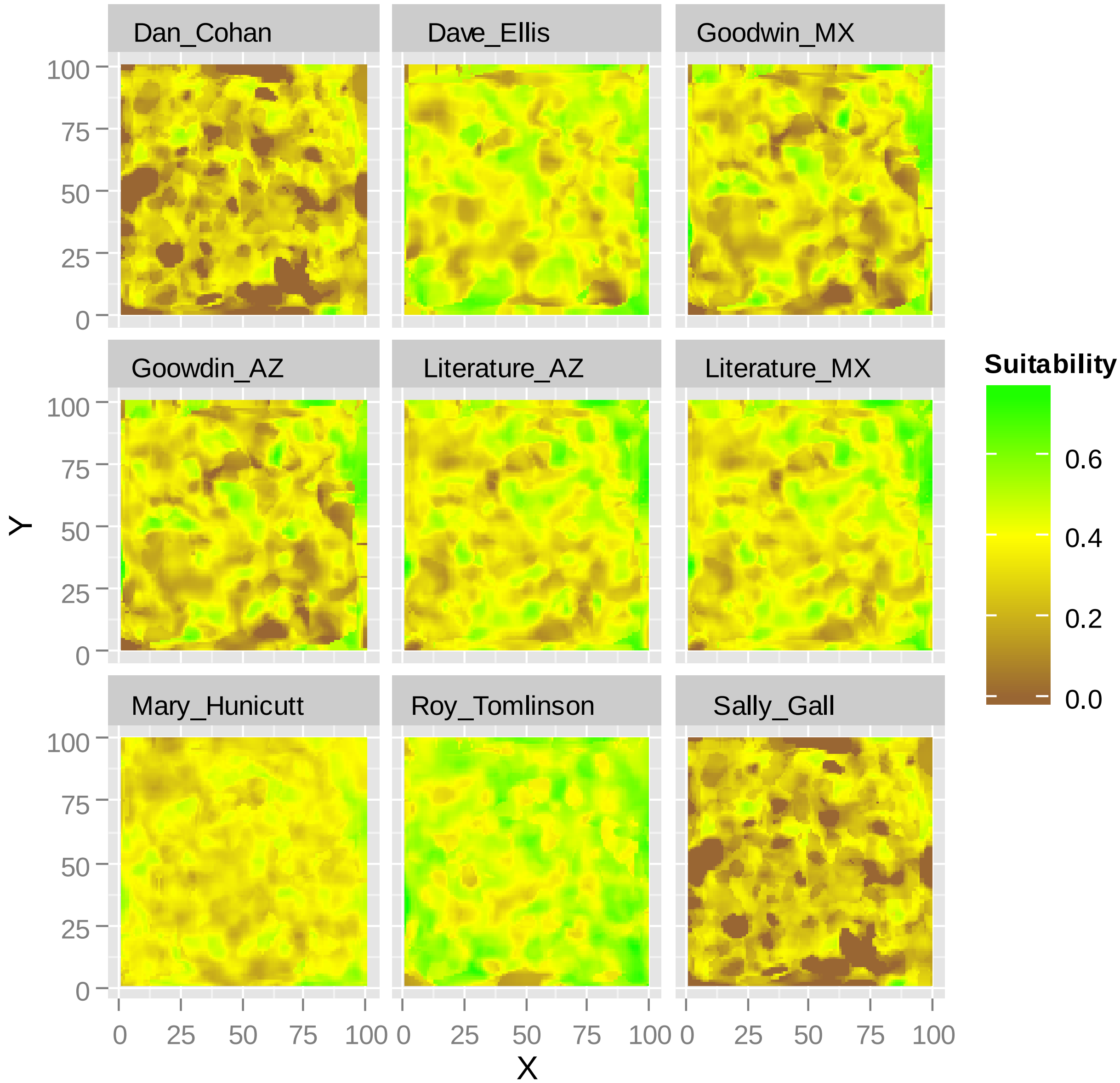


Figure 6. Habitat suitability scores from the 9 HSI models applied to the same suitability functions. This simulation bypassed the individual suitability scores for each model and instead gave each model the same score (centered symmetrically at 0.5) for each input variable. The only difference between the 9 models was the structure of the model. The differences in functional forms among models produced substantial differences in model outputs.

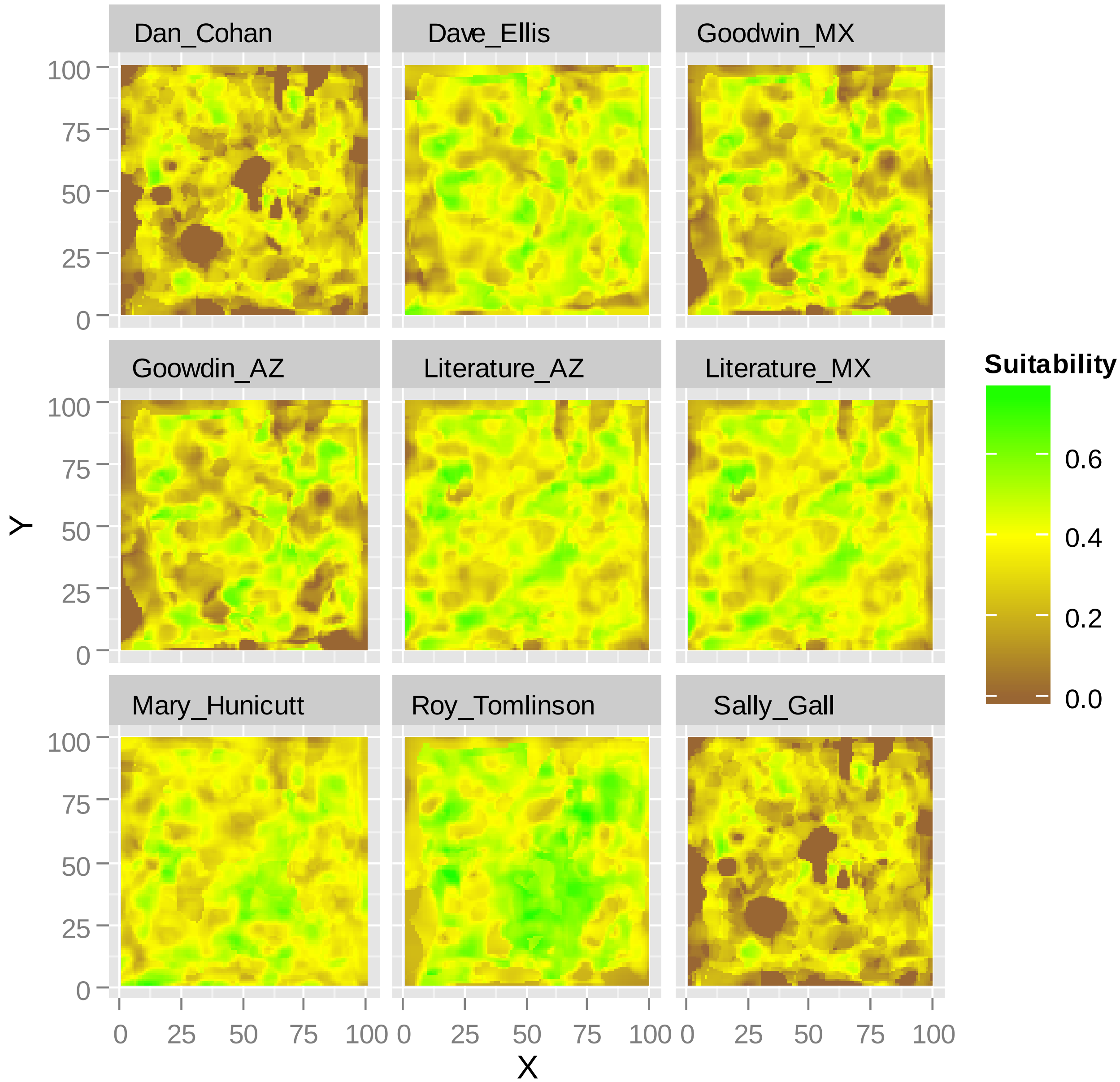


Figure 7. Overall habitat suitability scores from the 9 HSI models from the second simulation of suitability scores. Results from this simulation are similar to the other two.

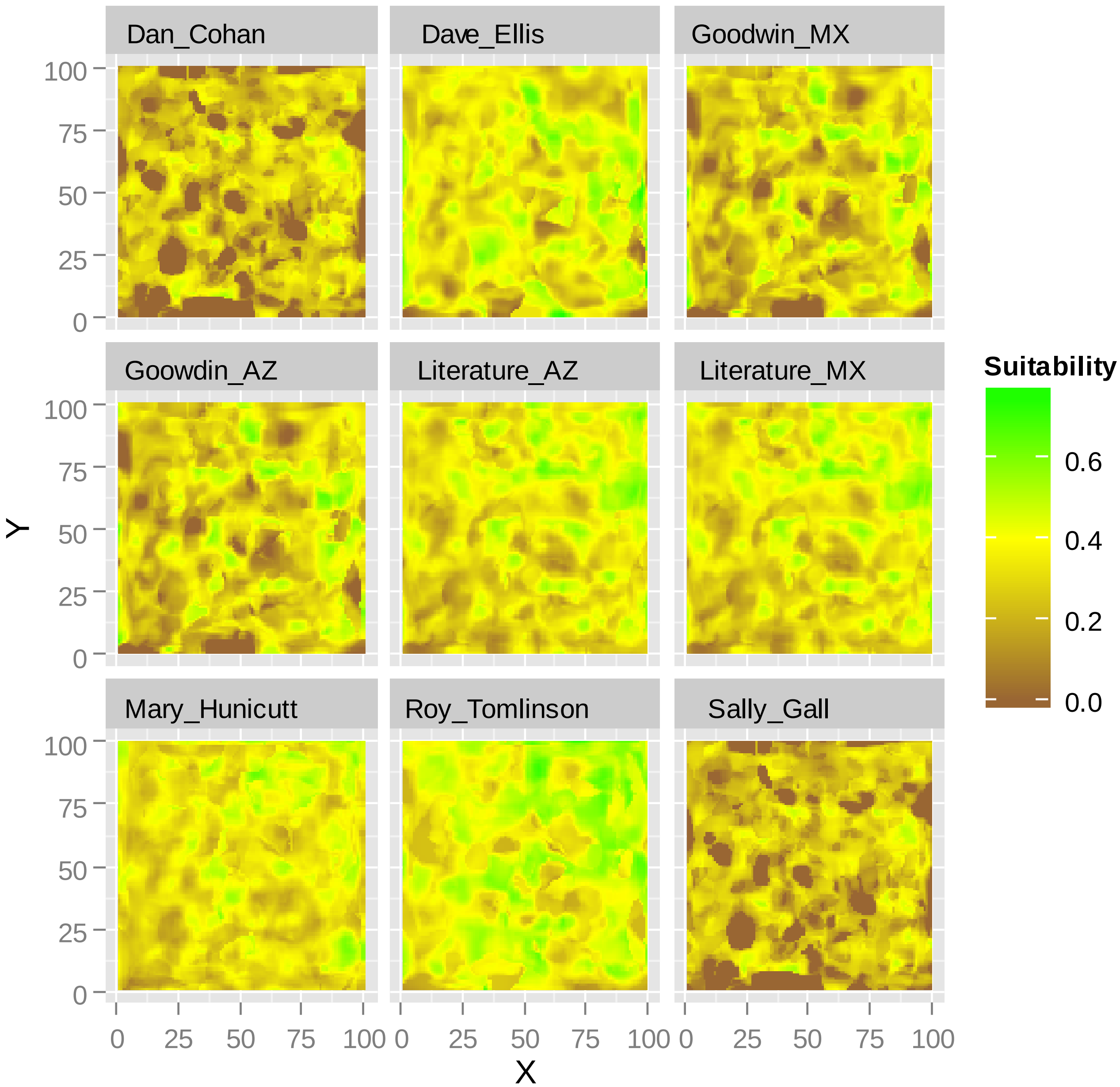


Figure 8. Overall habitat suitability scores from the 9 HSI models from the 3rd simulation of suitability scores. Results from this simulation are similar to the other two.

	Simulation 1				Simulation 2				Simulation 3				Average		
Author	Mean	Min	Max	Variance	Mean	Min	Max	Variance	Mean	Min	Max	Variance	Mean	Range	Variance
Dan Cohan	0.237	0.000	0.672	0.018	0.251	0.000	0.646	0.020	0.220	0.000	0.541	0.017	0.236	0.620	0.018
Dave Ellis	0.399	0.000	0.709	0.013	0.380	0.000	0.673	0.013	0.362	0.000	0.756	0.012	0.380	0.713	0.013
J. Goodwin (MX)	0.323	0.000	0.767	0.018	0.317	0.000	0.705	0.021	0.286	0.000	0.662	0.017	0.309	0.711	0.019
J. Goodwin (AZ)	0.323	0.000	0.767	0.018	0.317	0.000	0.705	0.021	0.286	0.000	0.662	0.017	0.309	0.711	0.019
Mary Hunnicutt	0.358	0.128	0.627	0.005	0.383	0.081	0.730	0.009	0.340	0.074	0.641	0.007	0.360	0.572	0.007
Sally Gall	0.227	0.000	0.672	0.016	0.243	0.000	0.646	0.019	0.212	0.000	0.538	0.015	0.227	0.619	0.017
Roy Tomlinson	0.474	0.129	0.783	0.008	0.441	0.113	0.769	0.015	0.418	0.108	0.733	0.010	0.444	0.645	0.011
Literature (AZ)	0.386	0.000	0.776	0.013	0.388	0.015	0.712	0.012	0.346	0.074	0.659	0.011	0.373	0.686	0.012
Literature (MX)	0.386	0.000	0.776	0.013	0.388	0.015	0.712	0.012	0.346	0.074	0.659	0.011	0.373	0.686	0.012

Table 4. Summary statistics from the 9 HSI models applied to the same suitability scores for individual variables. Models from the literature and John Goodwin were equivalent between Arizona and Mexico after eliminating the individual suitability functions. John Goodwin's model (the functional form) had the highest variance indicating that it can discriminate well between low- and high-quality habitat. Two other models (Sally Gall and Dan Cohan) also had functional forms that did a good job of discriminating between low- and high-quality habitat.

Author	Simulation 1				Simulation 2				Simulation 3			
	Mean	Min	Max	Variance	Mean	Min	Max	Variance	Mean	Min	Max	Varian
Dan Cohan	0.149	0.000	0.609	0.012	0.193	0.000	0.656	0.017	0.194	0.000	0.692	0.013
Dave Ellis	0.054	0.000	0.559	0.008	0.068	0.000	0.623	0.011	0.051	0.000	0.546	0.009
J. Goodwin (MX)	0.405	0.008	0.876	0.020	0.313	0.000	0.774	0.020	0.339	0.037	0.888	0.033
J. Goodwin (AZ)	0.277	0.039	0.790	0.020	0.278	0.037	0.864	0.021	0.294	0.000	0.821	0.024
Mary Hunnicutt	0.316	0.077	0.616	0.012	0.287	0.076	0.611	0.012	0.280	0.078	0.646	0.011
Sally Gall	0.263	0.019	0.609	0.013	0.232	0.019	0.596	0.013	0.223	0.019	0.589	0.012
Roy Tomlinson	0.578	0.027	0.714	0.011	0.581	0.124	0.713	0.009	0.583	0.139	0.796	0.007
Literature (AZ)	0.051	0.005	0.342	0.001	0.040	0.000	0.355	0.001	0.063	0.002	0.414	0.002
Literature (MX)	0.152	0.000	0.574	0.011	0.181	0.000	0.706	0.017	0.182	0.000	0.692	0.013

Table 5. Summary statistics of HSI scores for the 9 models from three computer simulations. Summary statistics were nearly constant across the simulations indicating that all of the HSI models are robust against small variations in data, as would be expected from measurement error. Both of John Goodwin's models had the largest range of scores whereas Roy Tomlinson's model had the smallest range of scores. A large range of scores indicates the ability of a model to discriminate between low- and high-quality habitat. However, differences in ranges between the models listed above could be an artifact of the data simulation and may differ if parameters of the simulation changed.

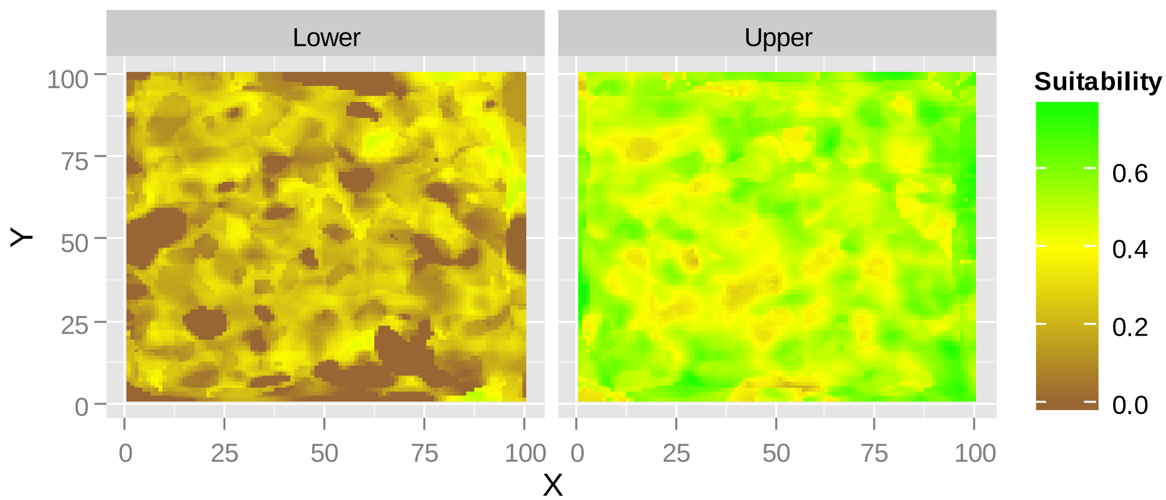


Figure 9. Upper and lower habitat suitability confidence intervals from the third simulation of environmental variables. Lower confidence intervals can be used as a conservative estimate of habitat suitability for masked bobwhites until further research has reduced the uncertainty around suitability estimates.

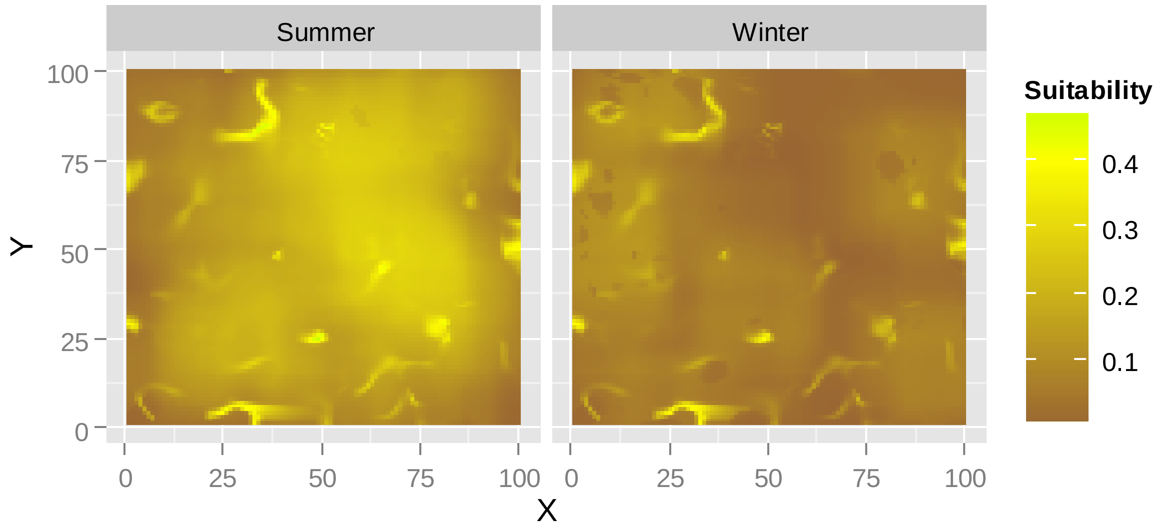


Figure 10. Habitat suitability of the same area in both winter and summer according to Roy Tomlinson's model. Since the overall suitability of this area is determined by the minimum suitability of these two seasons, it would be pointless to attempt to improve summer habitat without addressing the deficiency in winter habitat. This example shows how examining suitability scores at multiple levels within a model can help direct limited research dollars to achieve maximal impact for improving overall habitat suitability.

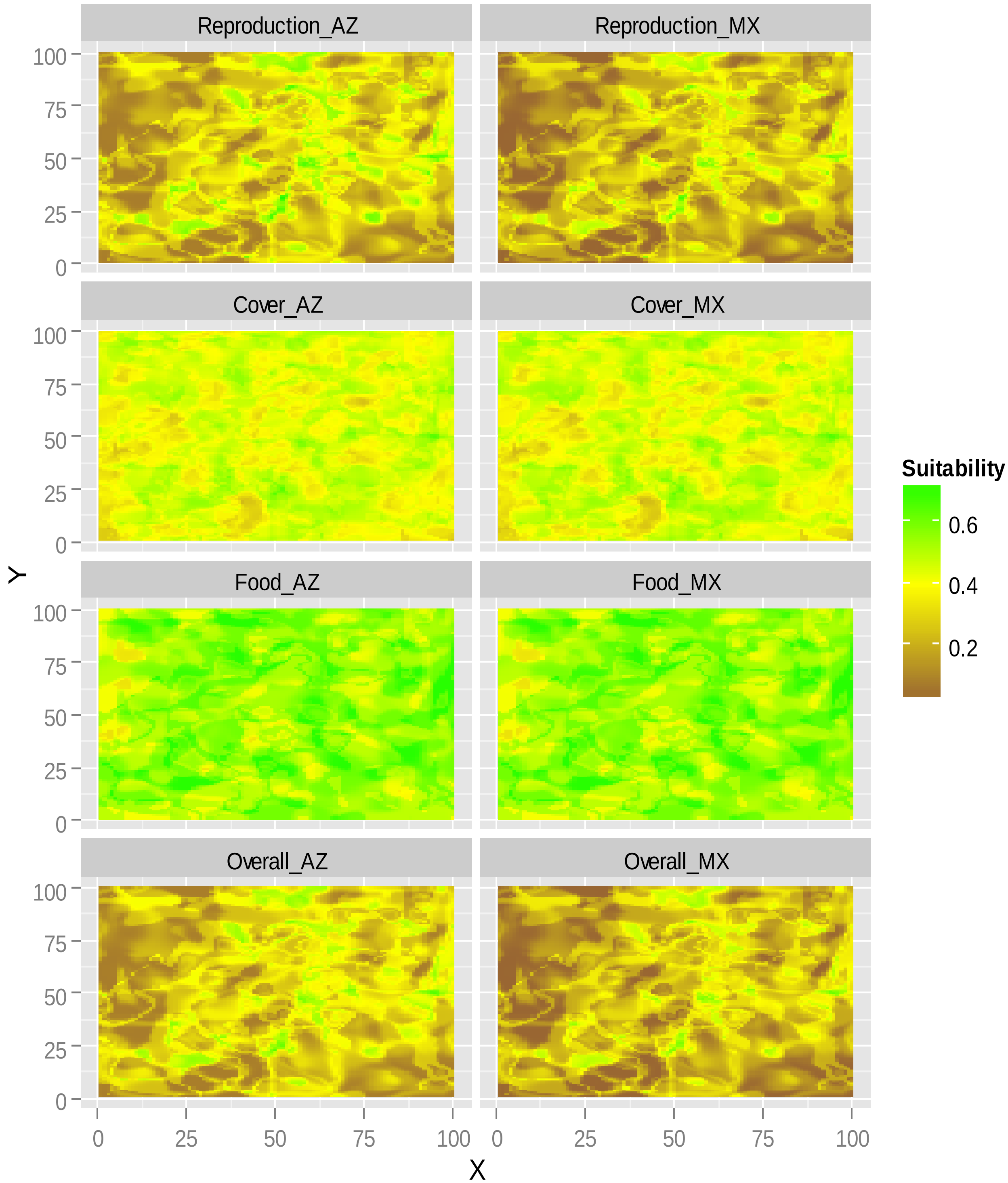


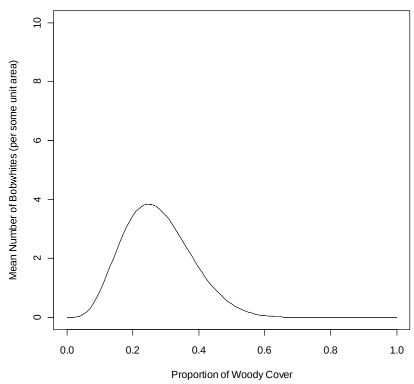
Figure 11. Habitat suitability plots of each major habitat component from the HSI model derived from information in the literature. Examining models applied to actual environmental data in this way allows managers to identify which components of the habitat are most limiting. In this case, which is based on simulated data, it is clear that environmental variables related to reproduction are the limiting component of the HSI model.

Appendix A:

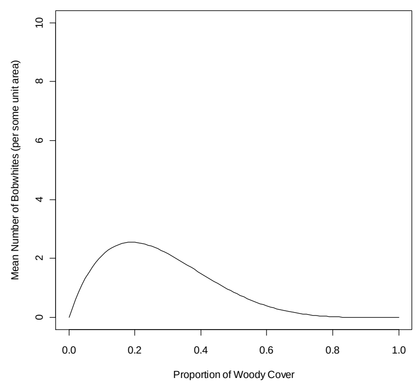
Below are the graphical representations of the potential relationships between 5 habitat variables and habitat suitability for masked bobwhites. We used means (and ranges) of variables from our interviews with species experts and from the published literature to produce a suite of potential relationships for each variable. In cases where a species expert or published article provided a mean but no range, we produced three graphs with varying degrees of variance: high, medium, and low. In cases where a species expert or published article provided a range but no mean, we created graphs with varying levels of kurtosis (skew) to create various means (low, centered, and high) within a given range. The number of graphs produced for each variable reflects either the degree of uncertainty about the relationship, or the diversity of opinions among species experts, or both. For all beta densities listed below, the beta function ($B(\alpha,\beta)$) is defined as:

$$B(\alpha,\beta) = \int_0^1 x^{\alpha-1}(1-x)^{\beta-1}dx$$

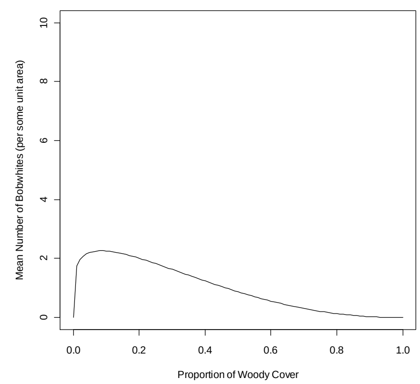
<u>Woody Cover (Brush and Shrub)</u>



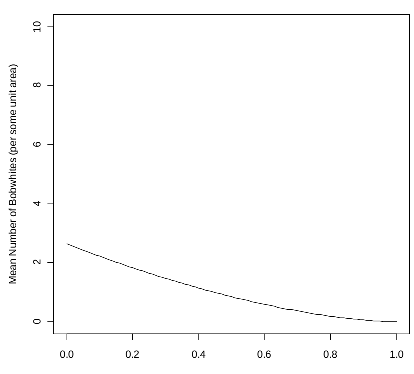
$$\frac{1}{B(5,13.12)}x^4(1-x)^{12.1}$$



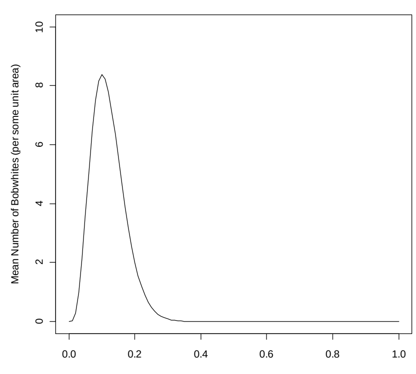
$$\frac{1}{B(2,5.27)}x(1-x)^{4.27}$$



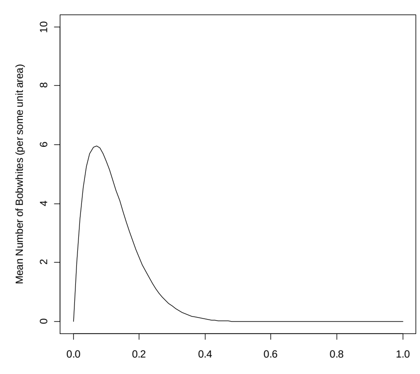
$$\frac{1}{B(1.2,3.16)}x^{0.2}(1-x)^{2.16}$$



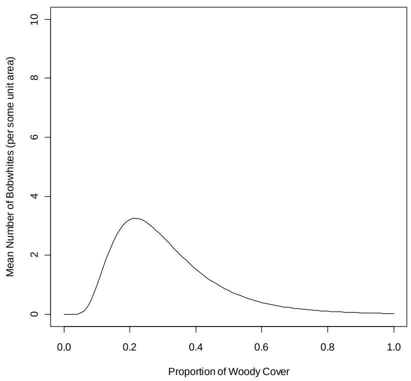
$$\frac{1}{B(1,2.64)}(1-x)^{1.64}$$



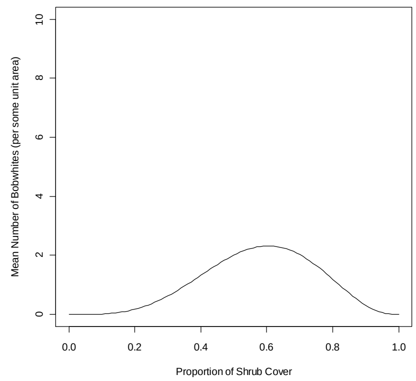
$$\frac{1}{B(5,36.66)}x^4(1-x)^{35.7}$$



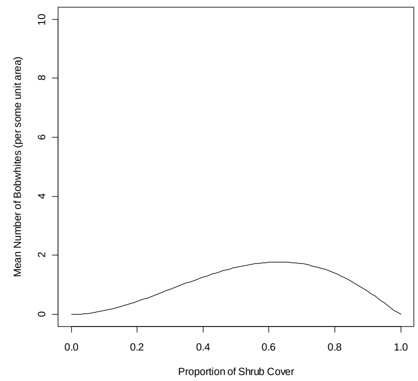
$$\frac{1}{B(2,14.67)}x(1-x)^{13.7}$$



$$\frac{1}{0.5x\sqrt{2\pi}}e^{-(lnx+1.28)^2}$$

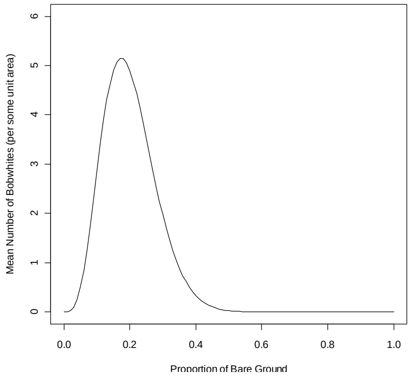


$$\frac{1}{B(5,3.62)}x^4(1-x)^{2.62}$$

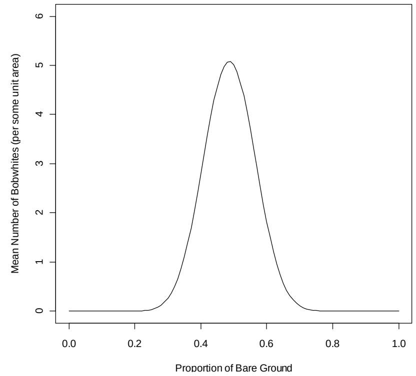


$$\frac{1}{B(3,2.17)}x^2(1-x)^{1.17}$$

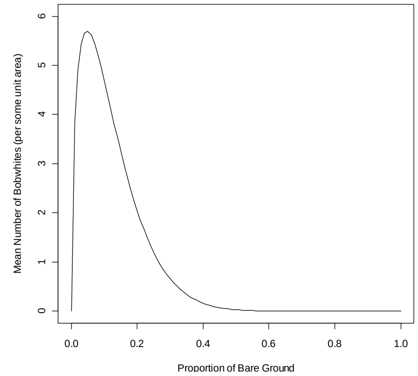
Bare Ground



$$\frac{1}{B(5,20)}x^4(1-x)^{19}$$

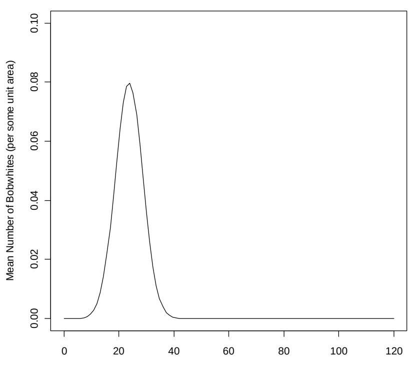


$$\frac{1}{B(20,21.1)}x^{19}(1-x)^{20.1}$$

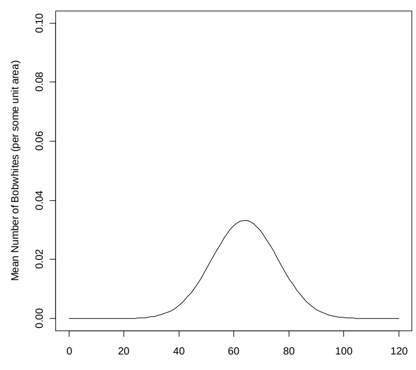


$$\frac{1}{B(1.5,11)}x^{0.5}(1-x)^{10}$$

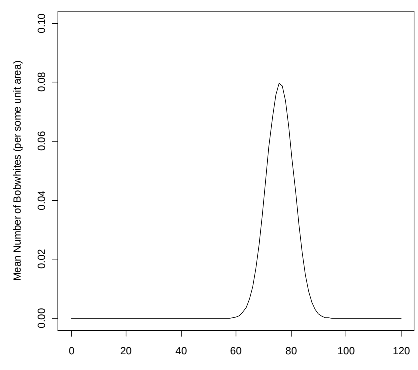
Nest Substrate Height



$$\frac{1}{5\sqrt{2\pi}}e^{\frac{-(x-23.7)^2}{50}}$$

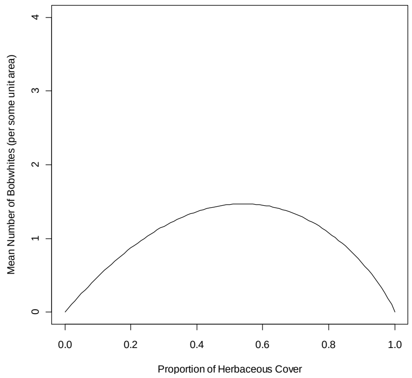


$$\frac{1}{12\sqrt{2\pi}}e^{\frac{-(x-64)^2}{144}}$$

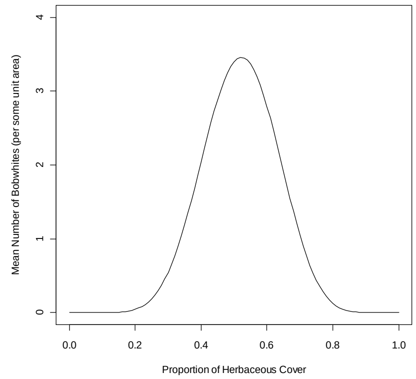


$$\frac{1}{5\sqrt{2\pi}}e^{\frac{-(x-76)^2}{25}}$$

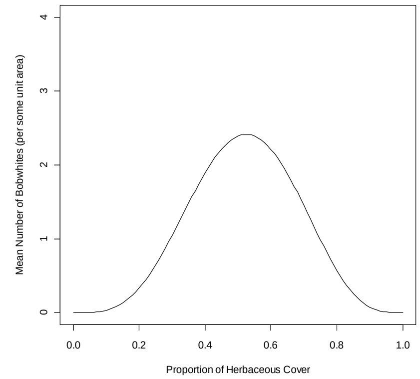
Herbaceous Cover



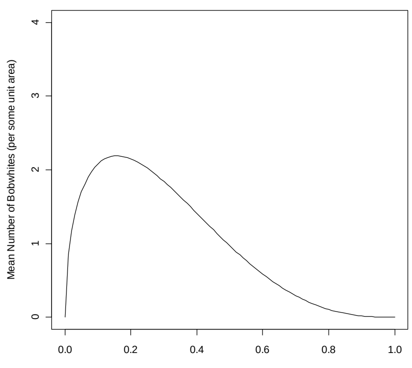
$$\frac{1}{B(2,1.85)}x(1-x)^{0.85}$$



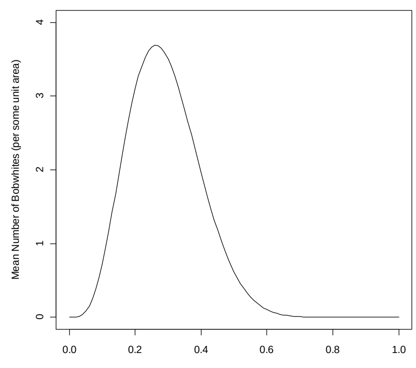
$$\frac{1}{B(10,9.23)}x^{9}(1-x)^{8.23}$$



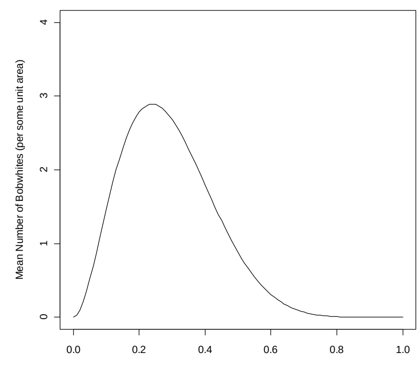
$$\frac{1}{B(5,4.62)}x^{4}(1-x)^{3.62}$$



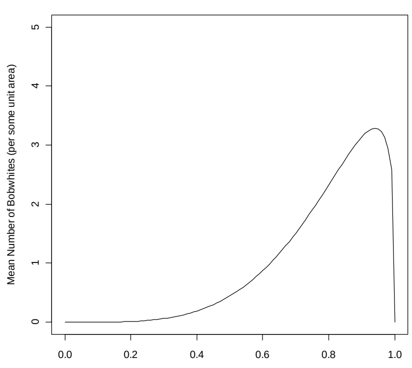
$$\frac{1}{B(1.5,3.67)}x^{0.5}(1-x)^{2.67}$$



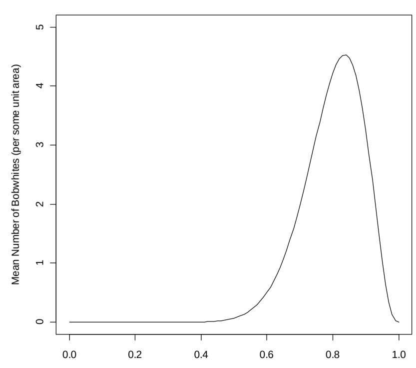
$$\frac{1}{B(5,12.24)}x^{4}(1-x)^{11.24}$$



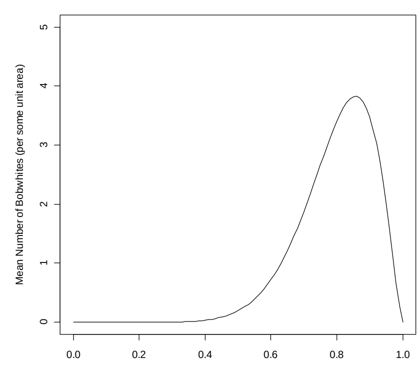
$$\frac{1}{B(3,7.34)}x^{2}(1-x)^{6.34}$$



$$\frac{1}{B(5,1.25)}x^{4}(1-x)^{0.25}$$

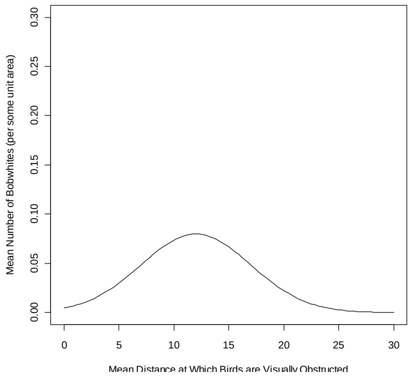


$$\frac{1}{B(15,3.75)}x^{14}(1-x)^{2.75}$$

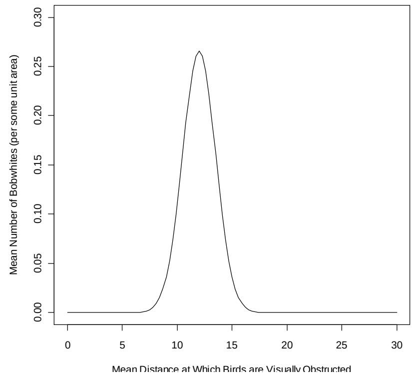


$$\frac{1}{B(10,2.5)}x^{9}(1-x)^{1.5}$$

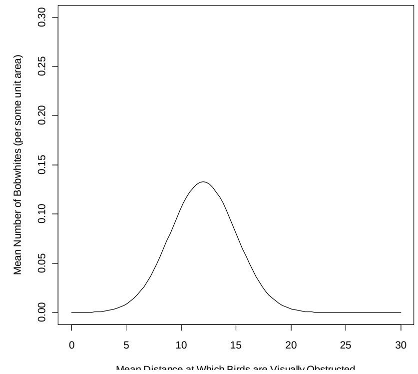
<u>Visual Obstruction (at ground level)</u>



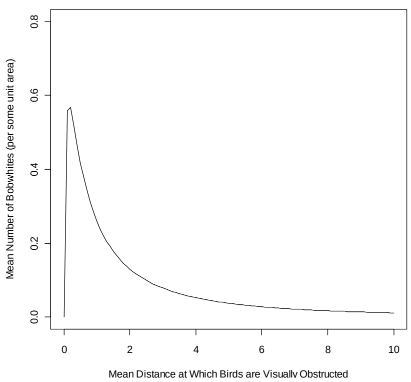
$$\frac{1}{5\sqrt{2\pi}}e^{\frac{-(x-12)^2}{50}}$$



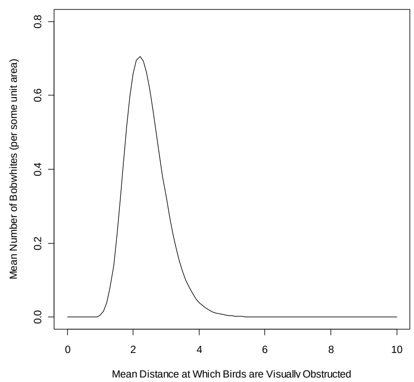
$$\frac{1}{1.5\sqrt{2\pi}}e^{\frac{-(x-12)^2}{2.25}}$$



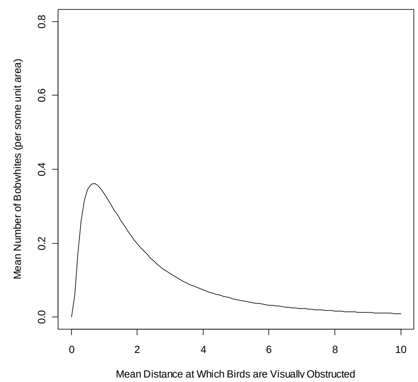
$$\frac{1}{3\sqrt{2\pi}}e^{\frac{-(x-12)^2}{9}}$$



$$\frac{1}{1.5x\sqrt{2\pi}}e^{\frac{-(lnx-0.349)^2}{4.5}}$$



$$\frac{4}{x\sqrt{2\pi}}e^{-8(lnx-0.8486)^2}$$



$$\frac{1}{x\sqrt{2\pi}}e^{\frac{-(lnx-0.599)^2}{2}}$$

Appendix B

Habitat Suitability Index Model: Dr. David Ellis

The following habitat suitability index model is the result of information obtained from a single species expert. We developed this model following the U.S. Fish and Wildlife Service guide to the development of habitat suitability index (HSI) models 103-ESM (USFWS 1981). However, unlike typical HSI models this model is intended to be used in conjunction with alternative HSI models developed from additional experts and existing literature. This model represents the best estimates of a single species expert.

1.Model Applicability:

1.1 Geographic area. This model was developed based on knowledge of masked bobwhite habitat in Arizona, specifically Buenos Aires National Wildlife Refuge.

1.2 Season. This model was developed to evaluate habitat needs of masked bobwhites over the entire year.

2. Model Description:

2.1 Overview. This model considers the ability of assessed habitat to meet the food, reproductive, and cover requirements of masked bobwhite as an indicator of overall habitat suitability. All components of the model are assessed by vegetative conditions. The relationship between habitat variables and critical life history requirements of masked bobwhite is illustrated in Figure 1.

2.2 Written Documentation.

The following sections provide a written documentation of the logic and assumptions used to interpret the habitat information for masked bobwhite in order to explain the variables and equations that are used in the HSI model. We present each critical habitat requirement and describe the variables which contribute to it.

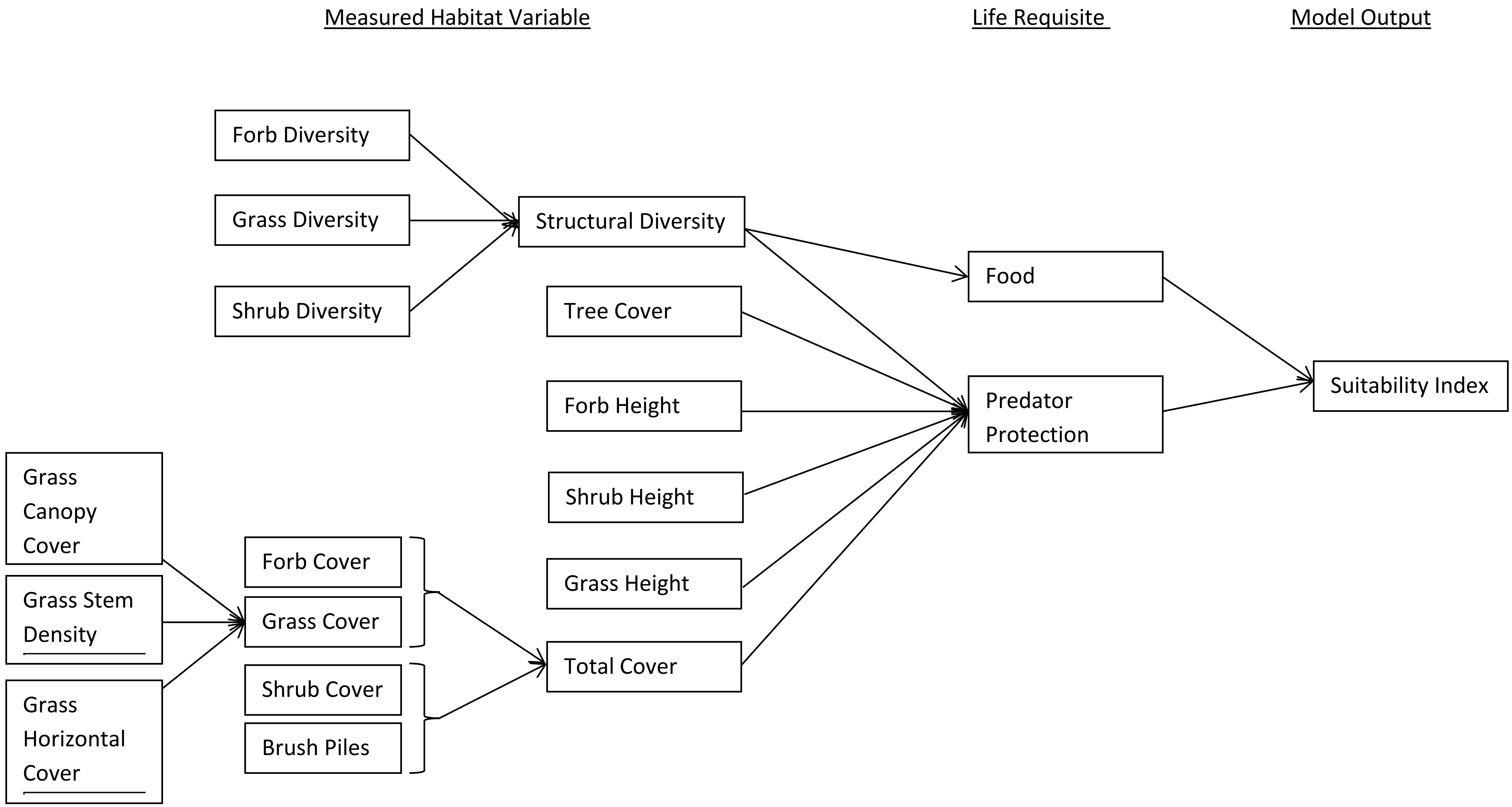
1. Reproduction. Reproductive requirements are assumed to be met if all the other critical habitat requirements are adequately addressed.

2. Food. Structural diversity is important and is a function of the species diversity of grasses, forbs, and shrubs. Adequate diversity is important for providing food year-round and can be measured via Shannon Diversity Index or similar method. Forb diversity is important for captive bred "uncultured' masked bobwhites. Released birds don't know how to utilize available food so it is important to have high diversity of forbs. This will increase the diversity of seed, vegetative, and arthropod food sources available to masked bobwhites over a greater period of the year. Masked bobwhites require a minimum of approximately 15 forb species before habitat becomes suitable. Habitat suitability generally increases with increasing forb diversity up to a saturation point at which increased diversity has no effect on suitability. Likewise, grass diversity is also an important food source and follows the same habitat suitability curve as forb diversity. Both perennial and annual grass species are important for food and the optimal ratio is likely 1:1. More information is needed about the role of grass diversity as a food resource for masked bobwhites. Shrub diversity is not essential but may provide an additional source of food.

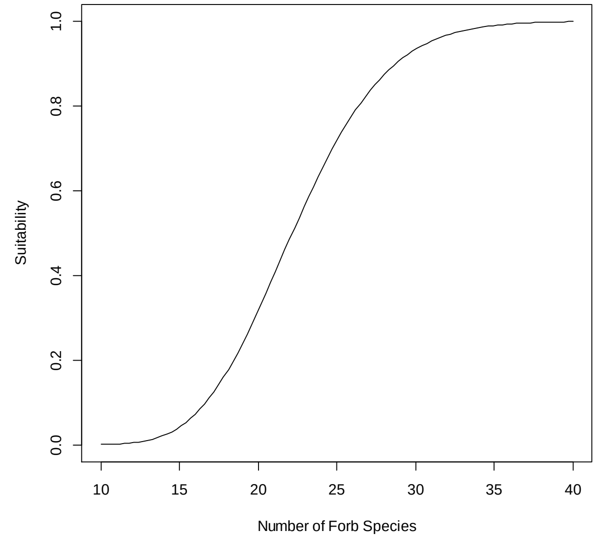
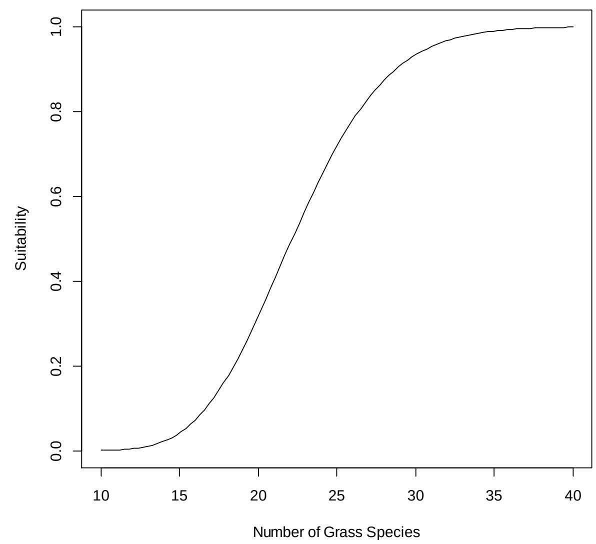
3. Predator Protection. There are two important components of predator protection; 1) concealment, and 2) physical barrier. Concealment is primarily a function of forbs and grasses. Forb height is important for concealment from predators. Optimal height of forbs is between 0.33 and 1 meter. Suitability diminishes both above and below this range. Likewise, forb cover is important as escape cover year round. Forb cover is assumed to be adequate if both total cover and forb diversity are adequate. Grass cover, primarily perennial grasses, is important for concealment. Suitable levels of grass cover can create safe corridors for birds to move on the landscape. Grass cover should be measured both as stem density and as percent ground cover from above since these two metrics will indicate the suitability of grass cover to provide the appropriate cover matrix. Additionally, grass cover should be measured from the side through the use of a cover board (or similar device) to ensure adequate concealment from terrestrial predators while allowing adequate mobility and visibility.

   Brush piles provide both concealment and a physical barrier and can be a replacement for natural cover if properly maintained. Brush piles should be placed approximately 45 meters apart and maintained to prevent collapse. Frames are recommended to prevent collapse of brush piles and maintain open space within the pile. Appropriate levels of shrub cover provide both concealment and physical barrier are preferable to brush piles and do not require regular maintenance. Moreover, shrub cover may provide additional benefits beyond that of predator protection (see Food). Shrubs should be between 0.33 and 2m in height to provide optimal protection from predators. As shrubs grow larger, and lose limbs which are close to the ground, they become less suitable habitat. Shrub cover is important year round but is most important during winter months. Total cover is a more important measure than any single cover metric. Total cover can be measured directly or can be computed from component parts as in Figure 1. Structural diversity creates both concealment and physical protection for masked bobwhites during the entire year while still providing adequate space for movement and visibility. Tree cover is counterproductive for masked bobwhite habitat as it provides perch sites for raptors.

Figure 1. The relationship between measured habitat variables, critical life history requirements, and habitat suitability for masked bobwhites.



3. Suitability Functions and Graphs

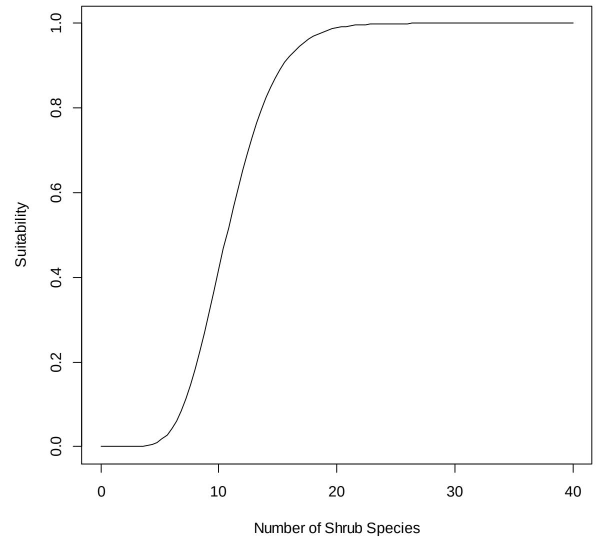
Variable	Description	Suitability Function	Suitability Graph
FD	Forb Diversity measured as the total number of forb species on a given home range throughout the year	$F(x) = \frac{\int_0^x t^{21.5} e^{-t} dt}{\Gamma(22.5)}$ (Gamma CDF with α=23.5, β=1)	
GD	Grass Diversity measured as the total number of both annual and perennial grass species on a given home range throughout the year	$F(x) = \frac{\int_0^x t^{21.5} e^{-t} dt}{\Gamma(22.5)}$ (Gamma CDF with α=23.5, β=1)	

ShD

Shrub diversity measured as the total number of shrub species on a given home range throughout the year

$$F(x) = \frac{\int_0^x t^9 e^{-t} dt}{\Gamma(10)}$$

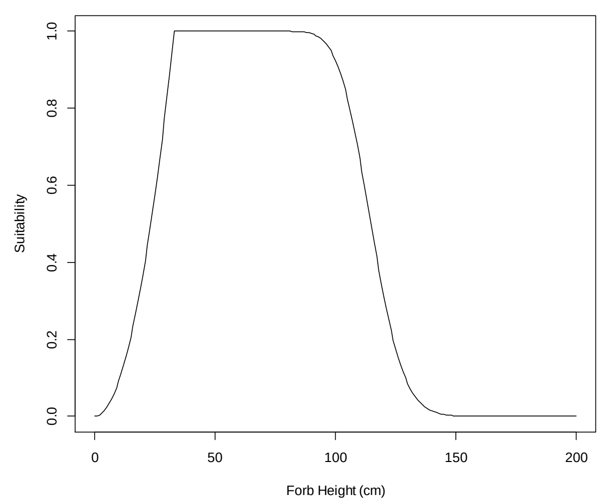
(Gamma CDF with α=11, β=1)



FH

Forb Height measured as the average height of Forbs on a given home range

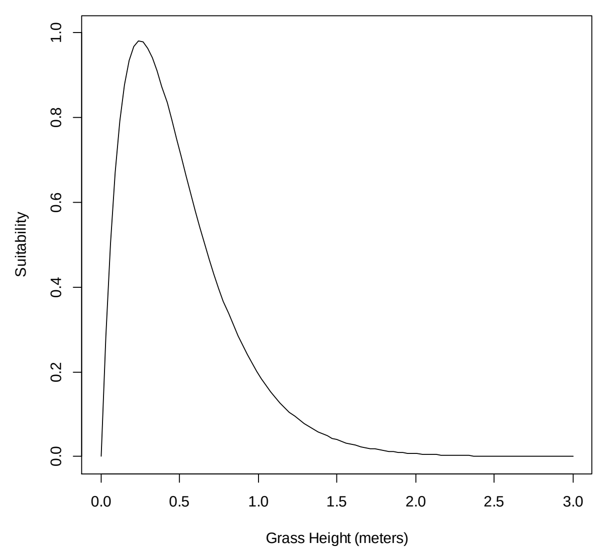
$$F(x) = \begin{cases} \frac{x^2}{1089} \; if \; x < 33 \\ 1 + \left(-\frac{\int_0^x t^{115} e^{-t} dt}{\Gamma(115)}\right) if \; x > 33 \end{cases}$$

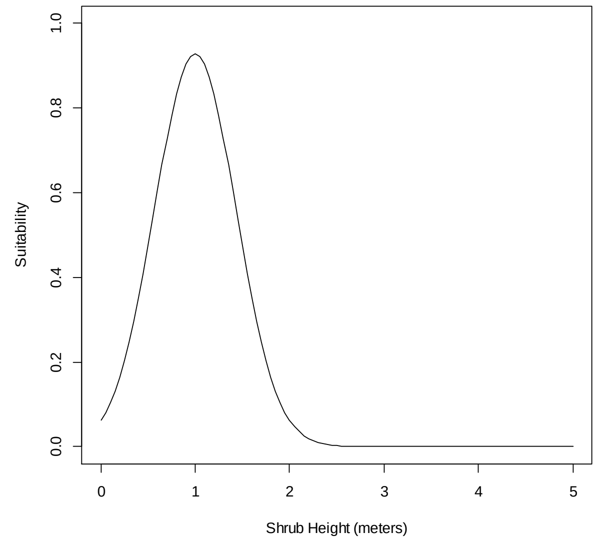
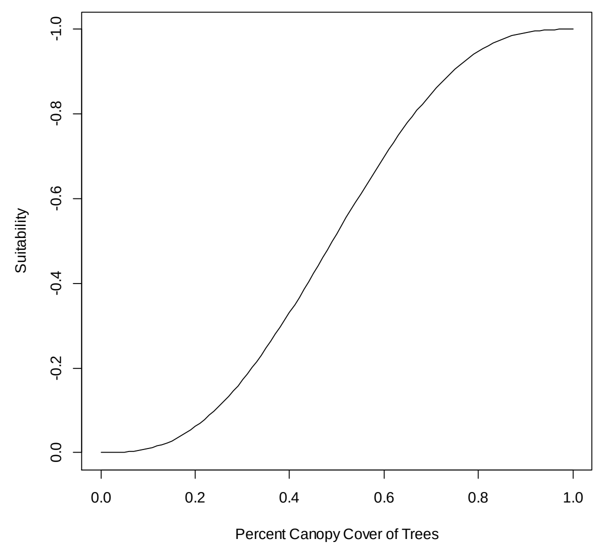
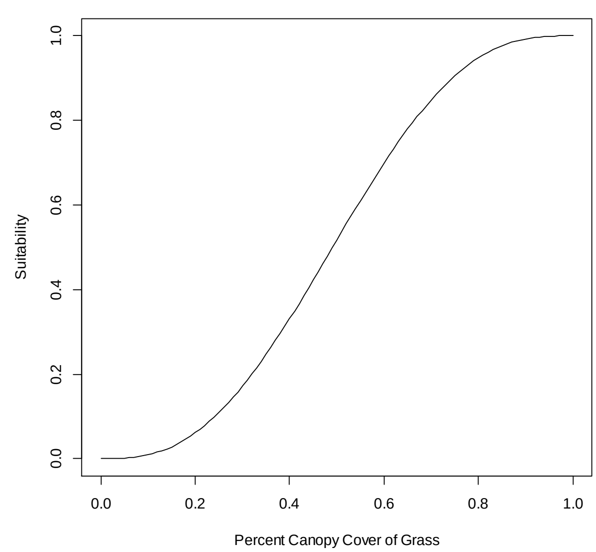


GH

Grass Height measured as the average height of grass on a given home range

$$F(x) = \left(\frac{x e^{-\frac{x}{4}}}{16}\right)/1.5$$

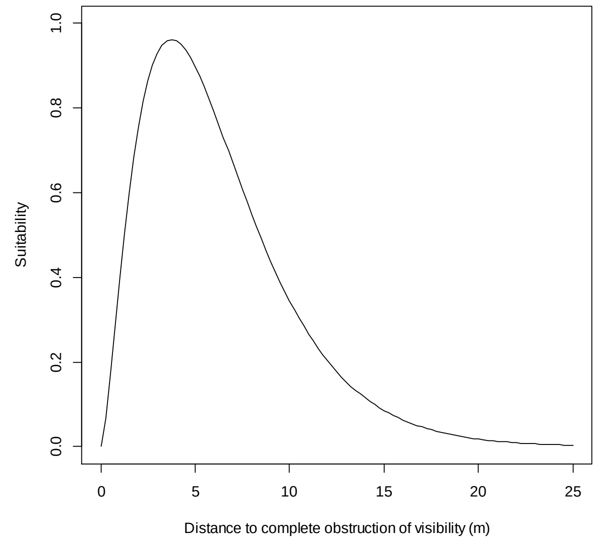


SH	Shrub Height measured as the average height of grass on a given home range	$F(x) = \frac{e^{-\frac{(x-1)^2}{0.3698}}}{\sqrt{.3698\pi}}$	
TrC	Tree cover measured as the percent canopy cover of trees on a given home range	$F(x) = -\frac{\int_0^x t^2(1-t)^{2.1}dt}{\int_0^1 e^2\,(1-t)^{2.1}dt}$	
GC1	Grass Canopy Cover measured from above the grass canopy as the amount of ground covered by grass foliage on a given home range	$F(x) = \frac{\int_0^x t^2(1-t)^{2.1}dt}{\int_0^1 e^2\,(1-t)^{2.1}dt}$	

GC2

Grass Cover from the side measured as the average amount of distance until complete visual obstruction on a given home range.

$$F(x) = \frac{x^{1.5}e^{-2.5x}}{0.1345}$$

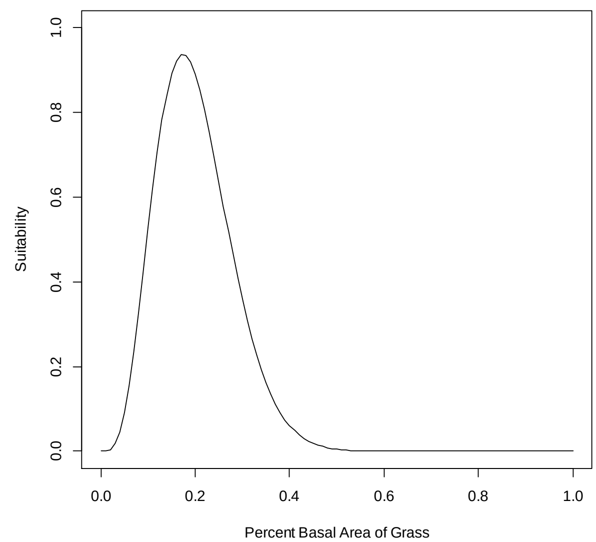


GC3

Grass basal area measured as the average area occupied by stems of grass on a given home range.

$$F(x) = \frac{x^4(1-x)^{19}}{B(5,20)}$$

(B(5,20) is the Beta function evaluated at α=5, β=20)



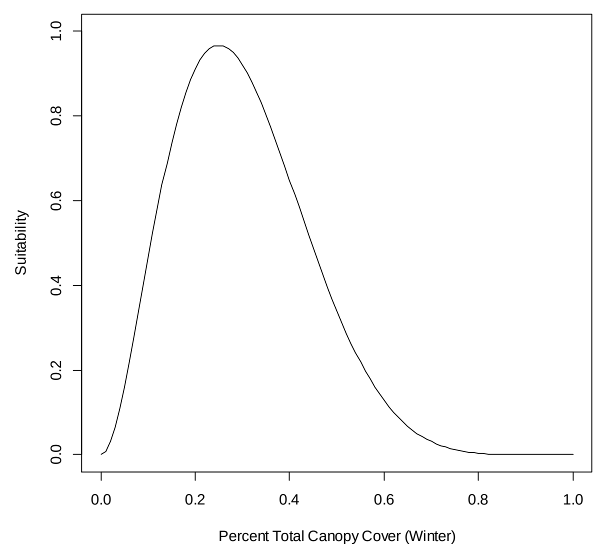
TC

Total Cover measured as the average total canopy cover of all vegetation (and brush piles) on a given home range. Suitability of total cover differs in winter and summer.

Winter:

$$F(x) = \frac{x^2(1-x)^6}{B(3,7)}$$

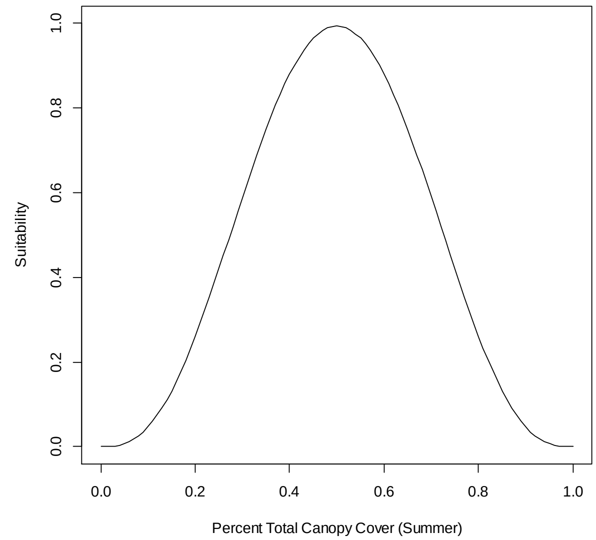
(B(3,7) is the Beta function evaluated at α=3, β=7)



Summer:

$$F(x) = \frac{x^3(1-x)^3}{B(4,4)}$$

(B(4,4) is the Beta function evaluated at α=3, β=7)



Equations.

The final habitat suitability index score is a result of the combination of suitability scores from component variables. The equations which describe this combination are governed by the assumptions and relationships described in section 2.2. Additive equations imply each variable in the equation can compensate for other variables with low scores unless otherwise noted. Multiplication implies a score of zero for any variable results in a suitability score equal to zero (i.e. both variables must have non-zero scores for the habitat to be suitable).

$$SD = \frac{FD + GD + ShD}{3}$$

$$GC = \frac{GC1 + GC2 + GC3}{3}$$

$$TC = [GC * SC]^{1/2}$$

$$Food = SD$$

$$Predator\ Protection = \left[\left(\frac{FH + GH + SH + TC + TrC}{5}\right) * SD\right]^{1/2}$$

$$HSI = Lowest\ score\ from\ Food\ or\ Predator\ Protection$$

Habitat Suitability Index Model: John Goodwin

The following habitat suitability index model is the result of information obtained from a single species expert. We developed this model following the U.S. Fish and Wildlife Service guide to the development of habitat suitability index (HSI) models 103-ESM (USFWS 1981). However, unlike typical HSI models this model is intended to be used in conjunction with alternative HSI models developed from additional experts and existing literature. This model represents the best estimates of a single species expert.

1.Model Applicability:

1.1 Geographic area. This model was developed based on knowledge of masked bobwhite habitat in both Arizona, specifically Buenos Aires National Wildlife Refuge, and northern Mexico. The habitat needs of masked bobwhites in Mexico and Arizona may differ for certain variables and this difference is reflected in the model below.

1.2 Season. This model was developed to evaluate habitat needs of masked bobwhites over the entire year.

2. Model Description:

2.1 Overview. This model considers the ability of assessed habitat to meet the food, reproductive, and cover requirements of masked bobwhite as an indicator of overall habitat suitability. All components of the model are assessed by vegetative conditions. The relationship between habitat variables and critical life history requirements of masked bobwhite is illustrated in Figure 1.

2.2 Written Documentation.

The following sections provide a written documentation of the logic and assumptions used to interpret the habitat information for masked bobwhite in order to explain the variables and equations that are used in the HSI model. We present each critical habitat requirement and describe the variables which contribute to it.

1. Reproduction. Adequate reproduction is essential to the recovery of the masked bobwhite. Reproduction of masked bobwhite in the wild must be successful enough to withstand substantial predation pressure. It is unclear whether reproductive success is currently limited by genetic weakness, poor habitat, or behavioral issues. This model is intended to address habitat conditions but it is recommended that all three of these potential problems are investigated. If available habitat provides adequate food, cover, and thermal refuge (described below) then the reproductive habitat needs of masked bobwhite are assumed to be met.

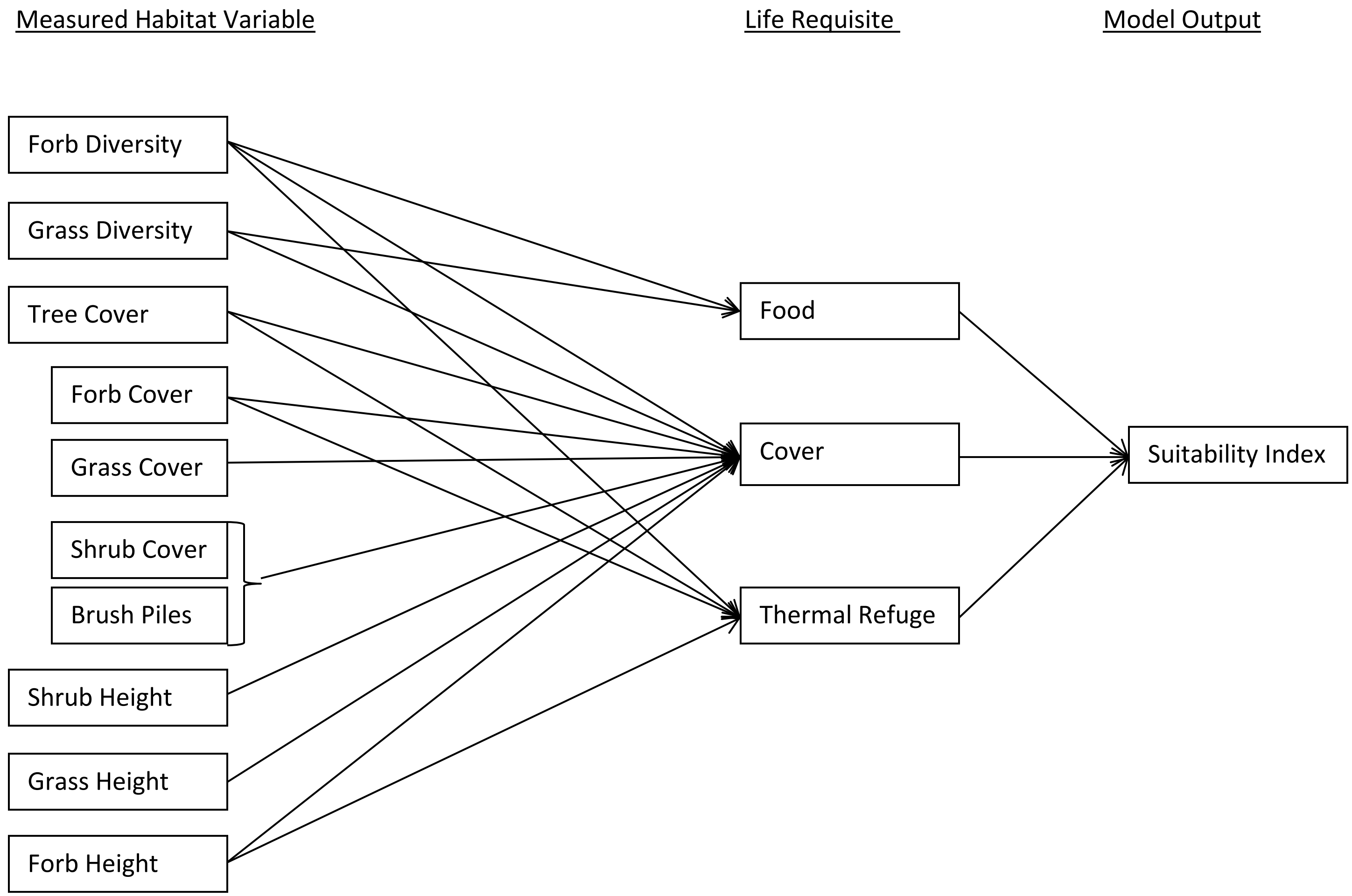
2. Food. Forb diversity is an important source of food for masked bobwhites. High forb diversity helps ensure habitat continuity by providing food during a larger portion of the year and during natural fluctuations in climate between years. A minimum of 10 to 15 species in reasonable abundance is necessary for adequate food while more is better. Grass diversity can also be an important source of food. Grass should be a mix of both perennials and annuals but perennials are more important. Large monocultures of any species are generally detrimental. Similar to forb diversity, a minimum of 10 to 15 grass species should be found in reasonable abundance across a given home range. In Mexico, higher forb diversity can make up for lower numbers of perennial grasses.

3. Cover. Forb diversity is important for providing adequate cover and habitat continuity as described above. Forb cover is an important component of masked bobwhite habitat. Optimal values of forb cover are lower in Arizona than Mexico. In Arizona 20 to 30 percent of the ground should be covered by forb canopy whereas in Mexico 30 and 40 percent of the ground should be covered by forb canopy. Forb cover should be composed of an adequate number of species as described for forb diversity. There is no optimal height for forbs, rather, forbs should have high structural diversity. High structural diversity is likely to be achieved if there are an adequate number of forb species present. Grass cover is an important substrate for nesting and loafing. Grass canopy cover is optimal between 20 and 30 percent. Grass diversity is important for maintaining adequate grass cover during dry years. Similar to forbs, grass should have high structural diversity. Large monocultures of any grass species are detrimental to masked bobwhite habitat. Shrub cover is also an important cover component and should be between 10 and 15 percent canopy cover. Additionally, shrub cover should be distributed in clumps across the landscape so that shrub patches are no more than 100 yards apart. Shrub height can vary quite a bit but should be above 3 or 4 feet. Brush piles can substitute for shrubs when shrubs are not available on the landscape or if there is inadequate shrub cover. Arroyos can also be valuable as movement corridors and tree cover can provide some level of cover as well. Bare ground is important for movement; 15 - 20 percent bare ground should be present in optimal habitat in Arizona and 30 - 40 percent bare ground should be present in optimal habitat in Mexico. The distribution of each cover component should be such that each component is available within approximately 100 yards.

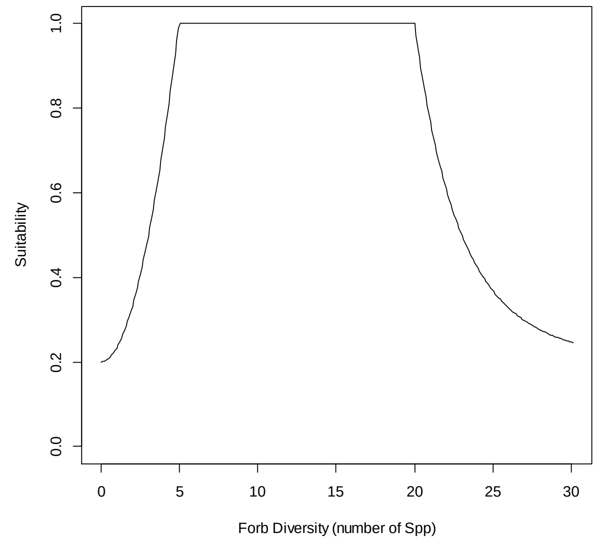
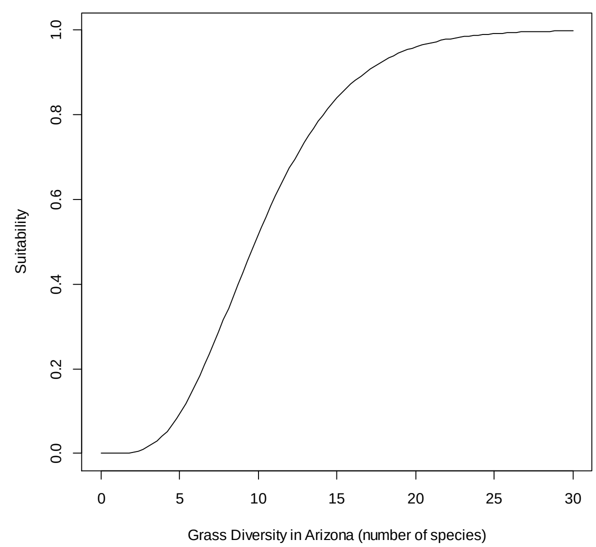
4. Thermal Refuge. Forb diversity and cover are both important for thermal regulation. Evapotranspiration from forbs can create a cooler microclimate under the forb canopy and

provide respite from high ambient temperatures. Forb diversity improves habitat continuity between and within years because high species diversity will result in a higher likelihood of having forb species which can tolerate a wide range of climactic conditions. Tree cover is also important for temperature and humidity regulation by providing shaded perches with greater airflow than is found on the ground.

Figure 1. The relationship between measured habitat variables, critical life history requirements, and habitat suitability for masked bobwhites.



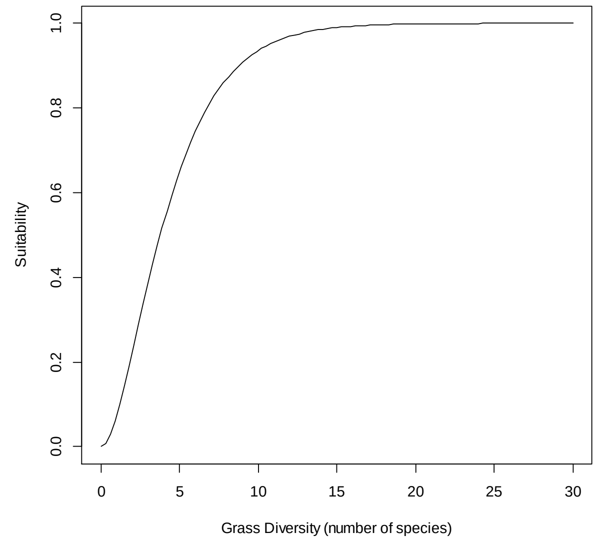
3. Suitability Functions and Graphs

Variable	Description	Suitability Function	Suitability Graph
FD	Forb Diversity measured as the total number of forb species found in reasonable abundance on a given home range throughout the year	$F(x) = \begin{cases} 0.2 + \frac{x}{5.5}^{2} & x < 5 \\ 1 & 5 < x < 20 \\ 0.2 + \frac{1.024e9}{x^7} & x > 20 \end{cases}$	
GD	Grass Diversity measured as the total number of both annual and perennial grass species found in reasonable abundance on a given home range throughout the year. Optimal levels of grass diversity differ in Arizona and Mexico.	Arizona: $F(x) = \frac{\int_0^{x/.476} t^4 e^{-t} dt}{\Gamma(5)}$ (Gamma CDF with α=5, β=0.476)	

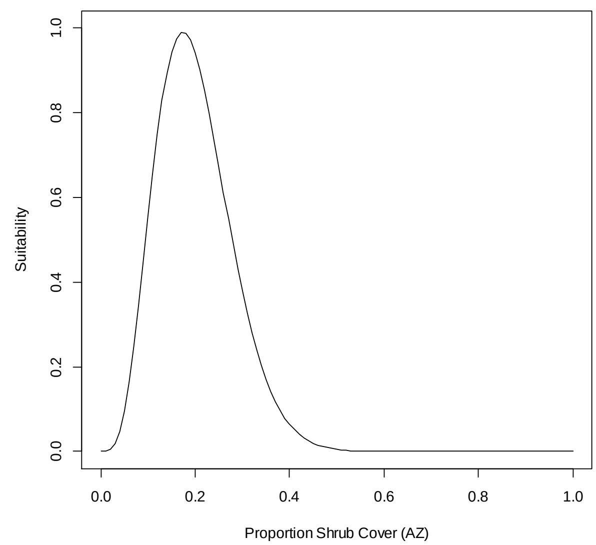
Mexico:

$$F(x) = \frac{\int_0^{x/.444} t^1 e^{-t} dt}{\Gamma(2)}$$

(Gamma CDF with α=2, β=0.444)

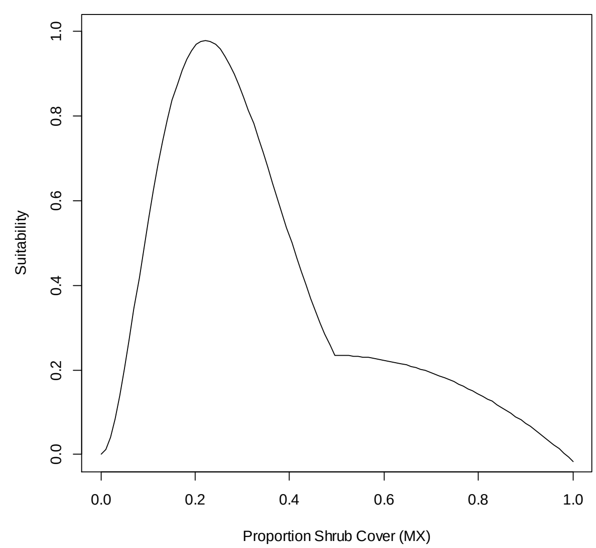


SC	Shrub cover measured as the average canopy cover of shrubs throughout the year. Shrub cover should be distributed in clumps approximately 100 yards apart.	Arizona: $$F(x) = \frac{x^4(1-x)^{19}}{B(5,20)}$$ (Beta PDF with α=5, β=20)



Mexico:

$$F(x) = \begin{cases} \frac{x^2(1-x)^{6.909}}{B(3,7.909)} & x \le .5 \\ x - x^2 - .0157 & .5 < x \end{cases}$$

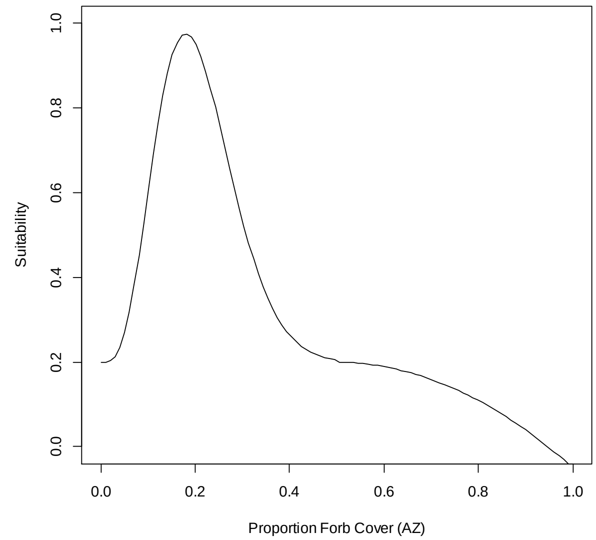


FC

Forb cover measured as the average canopy cover of forbs. Suitability differs in Arizona and Mexico.

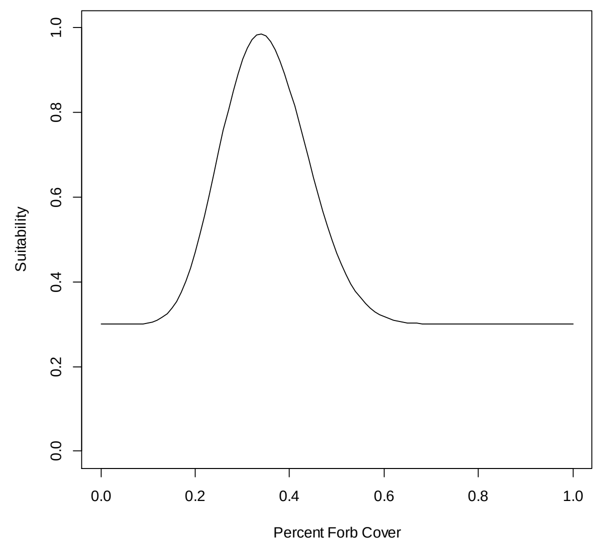
<u>Arizona:</u>

$$F(x) = \begin{cases} .2 + \dfrac{x^4(1-x)^{18}}{B(5,19)} * \dfrac{1}{6.4} & x \leq .5 \\ x - x^2 - .05, & x > .5 \end{cases}$$



<u>Mexico:</u>

$$F(x) = .3 + \frac{x^9(1-x)^{17.57}}{B(10,17.57)6.5}$$

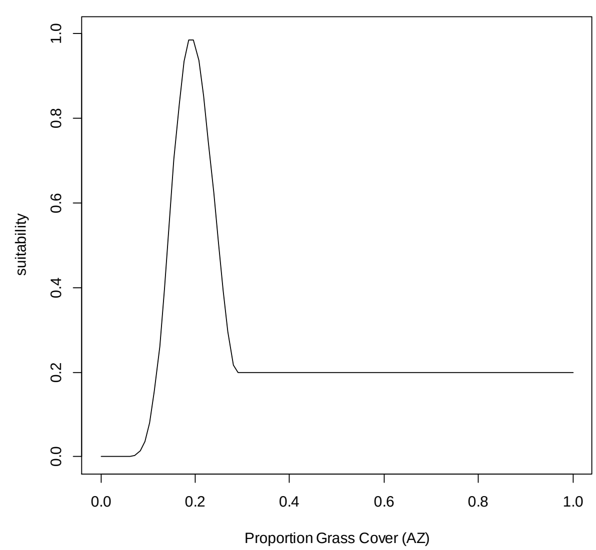


GC

Grass cover measured as the average canopy cover of grass. Suitability differs between Arizona and Mexico.

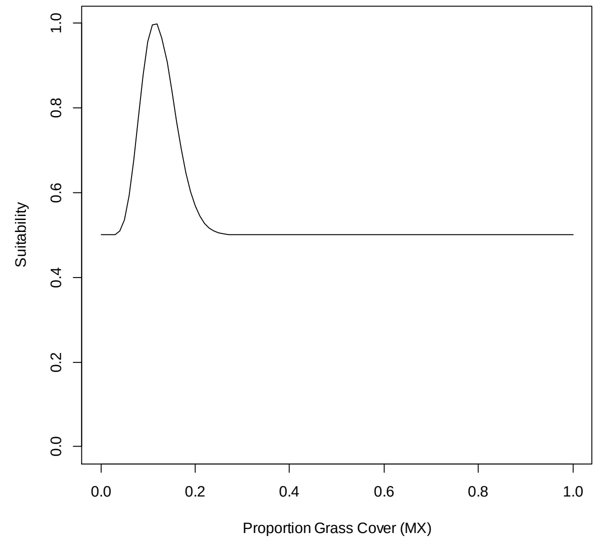
<u>Arizona:</u>

$$F(x) = \begin{cases} \dfrac{x^{14}(1-x)^{59}}{B(15,60)8.8}, & x \leq .28 \\ 0.2, & x > .28 \end{cases}$$



Mexico:

$$F(x) = .5 + \frac{x^9(1-x)^{59}}{B(10,60)22}$$

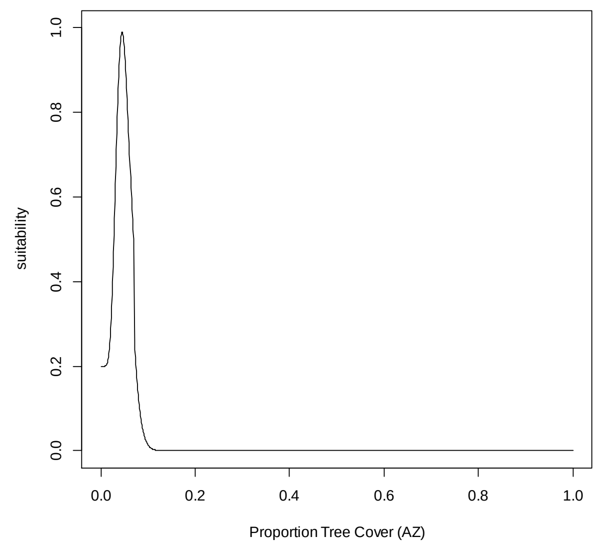


TC

Tree cover measured as the average canopy cover of trees. Suitability of tree cover differs between Arizona and Mexico.

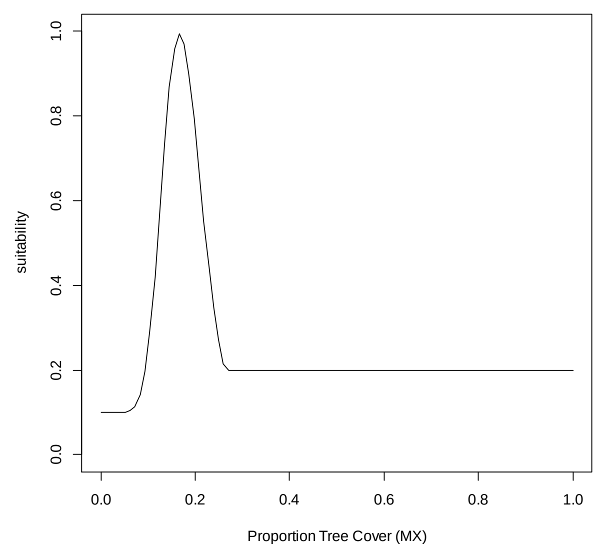
Arizona:

$$F(x) = \begin{cases} .2 + \dfrac{x^9(1-x)^{189}}{B(10,190)34}, x \leq .07 \\ \dfrac{x^9(1-x)^{189}}{B(10,190)34}, x > .07 \end{cases}$$



Mexico:

$$F(x) = \begin{cases} .1 + \dfrac{x^{14}(1-x)^{69.7}}{B(15,70.7)34}, x \leq .26 \\ 0.2, \quad x > .26 \end{cases}$$



Equations.

The final habitat suitability index score is a result of the combination of suitability scores from component variables. The equations which describe this combination are governed by the assumptions and relationships described in section 2.2. Additive equations imply each variable in the equation can compensate for other variables with low scores unless otherwise noted. Multiplication implies a score of zero for any variable results in a suitability score equal to zero (i.e. both variables must have non-zero scores for the habitat to be suitable).

$$Food = \frac{GD + FD}{2}$$

$$Cover = \frac{(FD * FC)^{1/2} + (GD * GC)^{1/2} + TC + SC}{4}$$

$$Thermal\ Refuge = \frac{(FD * FC)^{1/2} + TC}{2}$$

$$HSI = Lowest\ score\ from\ Food, Cover\ or\ Thermal\ Refuge$$

Habitat Suitability Index Model: Mary Hunnicutt

The following habitat suitability index model was created from the opinion of one species expert. We developed this model following the U.S. Fish and Wildlife Service guide to the development of habitat suitability index (HSI) models 103-ESM (USFWS 1981). However, unlike typical HSI models this model is intended to be used in conjunction with alternative HSI models developed from additional experts and existing literature. This model represents the best estimates of a single species expert.

Section 1.Model Applicability:

1.1 Geographic area. This model was developed based on knowledge of masked bobwhite habitat in Buenos Aires National Wildlife Refuge (BANWR), AZ, U.S. and nearby areas as well as the Rancho el Carrizo area south of Benjamin Hill, Sonora, MX.

1.2 Season. This model covers both breeding/nesting season (July-September) and post breeding (September-June).

Section 2. Model Description:

2.1 Overview. This model considers the ability of assessed habitat to meet the food, reproductive, and cover requirements of masked bobwhite as an indicator of overall habitat suitability. All components of the model are assessed by vegetative conditions. The relationship between habitat variables and critical life history requirements of masked bobwhite is illustrated in Figure 1.

2.2 Written Documentation.

The following sections provide a written documentation of the logic and assumptions used to interpret the habitat information for masked bobwhite in order to explain the variables and equations that are used in the HSI model. We present each critical habitat requirement and describe the variables which contribute to it.

1. **Cover**

This component provides both hiding cover and thermal cover for masked bobwhites. Overall canopy requirements are important, but species diversity and canopy structure may be even more important in providing what the bird needs.

Canopy cover requirements as determined by the HMP are:

- 15%-30% of woody vegetation cover (mid-story shrubs and trees 3 to 10 feet tall) (Johnson and Hoffman n.d.)
- ≥15% forb cover (Simms 1989)
- ≥15% native grass cover (Reichenbacher and Mills 1984)
- 0%-25% unobstructed bare ground (Goodwin and Hungerford 1977)

The tree component is not separated out from the shrub component because on BANWR there is very little shrub component available. Instead, small trees fulfill the habitat requirements otherwise satisfied by shrubs and are optimal at <10%-15% cover. However, leguminous shrubs are far more important to masked bobwhite than trees since leguminous shrubs provide a source of food as well as cover. Desert broom is not utilized by quail.

Cover should be composed of adequate species diversity. Diverse stands of native vegetation consisting of a minimum of 8-12 native perennial grass species; a minimum of 12-16 perennial forb species; and a minimum of 3-6 mid story shrub/tree species.

The structure of vegetative cover is also important for its efficacy. This structure is not well quantified, although Guthery (2001) described some portions using the vulnerability measures developed by Kopp et al. (1998). Good quality masked bobwhite habitat is multilayered and “clumpy” with a distinctive “lumpy” look. The term “lumpy” refers to the presence of multiple, overlapping, layers of vegetation. There should be tall components (typically trees), medium height components (typically shrubs), and a herbaceous component. The grass/forb (herbaceous) component sometimes stands alone, but it is often combined with interspersed areas of shrub mid-story and tree upper-story both with herbaceous understory. A substantial amount of bare ground is necessary, at least 25% and up to 50% in brood habitat. Bare ground should not be in blocks but, rather, should weave in and around clumps of vegetation to provide corridors for movement. Herbaceous cover should coalesce at the top while maintaining open space below to facilitate movement by masked bobwhites.

During the non-breeding season masked bobwhites are found almost exclusively in the edges between grasslands and woodlands. Even during the breeding season the birds may be nesting only a bit further away, indicating that edge habitat remains important during breeding. In Mexico, the drainangeges are very shallow and filled with whiteball acacia (*Acacia angustissima*) and bundleflower (*Desmanthus spp.*). In Arizona, the drainages were historically filled with sacaton grass which was likely used for both protection from predators and as a source of food (seeds). Unfortunately, most of the sacaton bottoms are gone, and very little protection from predators remains in drainages. Optimal drainages now contain *Mimosa* species, sometimes in combination with whiteball acacia, but also a wide variety of vines and forbs/grasses. Saltbush (*Atriplex spp.*) and whitethorn acacia (*Acacia constricta*) may also be beneficial.

Trees tend to be used for thermal cover and for males to call from during the breeding season. Coveys of masked bobwhites use the shade of trees for loafing habitat.

2. Food

a. Mexico – Food for masked bobwhites has been only rarely described. In Mexico there is a report of masked bobwhites feeding in a weedy garden with croton (*Croton spp.*), ragweed (*Ambrosia spp.*), and insects in their diet. Seeds of the appropriate size (generally considered to be the size of milo seed) are an important source of food. The availability of a variety of seeds species seems to be especially crucial, likely due to the progression of seed drop from the various species which provides continuous food throughout the year. In Mexico the main winter foods are white-ball acacia and bundleflower, of which there are at least two species. Both of these plants are abundant in the drainages. The bundleflower species appear to dehisce and drop seeds early in the fall while the white-ball acacia retains the pods on the plant for a longer into the winter. Almost all masked bobwhites sightings in Mexico outside of the breeding season are in association with drainages containing white-ball acacia and bundleflower indicating that the two plant species are important. There are many more leguminous shrubs in Mexico which are also likely to provide an important source of food.

b. Arizona- Arizona lacks large stands of white-ball acacia and bundleflower. However, masked bobwhites have been observed in the vicinity of small patches of these plants, suggesting masked bobwhites do utilize these species in Arizona. Alternatively, *Mimosa biuncifera* and *Mimosa dysocarpa* do occur in large stands in Arizona and their seeds appear to be of the right size for utilization by masked bobwhites. Moreover, masked bobwhites have been trapped in *Mimosa* stands adding to the evidence that these plants are useful habitat for masked bobwhites. Masked bobwhites have also been observed consuming the seeds of partridge pea (*Chamaecritae nictitans*) and, possibly though unconfirmed, showy vetch (*Vicia pulchella*) and vine mesquite grass (*Panicum obtusum*). Seeds are an important source of food in the winter through the early summer until the monsoonal rains occur. In the spring flight-pen bobwhites have been observed eating a wide variety of spouted vegetation except coyote gourd (*Curccurbita digitata*).

Forbs become abundant during the summer monsoon. Masked bobwhites appear to key in on grasshoppers, and other insects, during this period. Local abundance of grasshoppers is correlated with the presence of masked bobwhites. Chicks in captivity and been seen pursuing and consuming flour beetles within the commercial feed they are given at the day old stage. Crickets which are 2-weeks old, and approximately ¼ inch in (6mm) size, appeared to be the right size for 2-3 week old chicks. The timing of masked bobwhite breeding may be synchronized to the period when grasshoppers of this size are abundant. It is possible that climate change is altering the timing of grasshopper emergence and reducing the availability of this important source of food.

3. Reproduction (Courtship, nesting, and brood rearing)

Optimal habitat for masked bobwhites changes slightly during the monsoon reproduction season, expanding into the uplands. Abundance of masked bobwhites during the breeding season is associated with high species diversity of both herbaceous plants and leguminous shrubs. Males use shrubs (3-5 feet or .9-1.5 meters tall) and trees (20-30 feet or 6-9 meters tall) as calling sites. Males call from the tops of shrubs but will call from midway up trees (10-15 feet or 3-4.5 meters up).

Nests are typically located in a 9 inch (23cm) round clump of grass but can be located at the base of a shrub or under other similarly dense vegetation. In flight pens, masked bobwhites will even use artificial structures for nesting cover. Appropriate nest sites should be available at the rate of approximately 300-600 per acre.

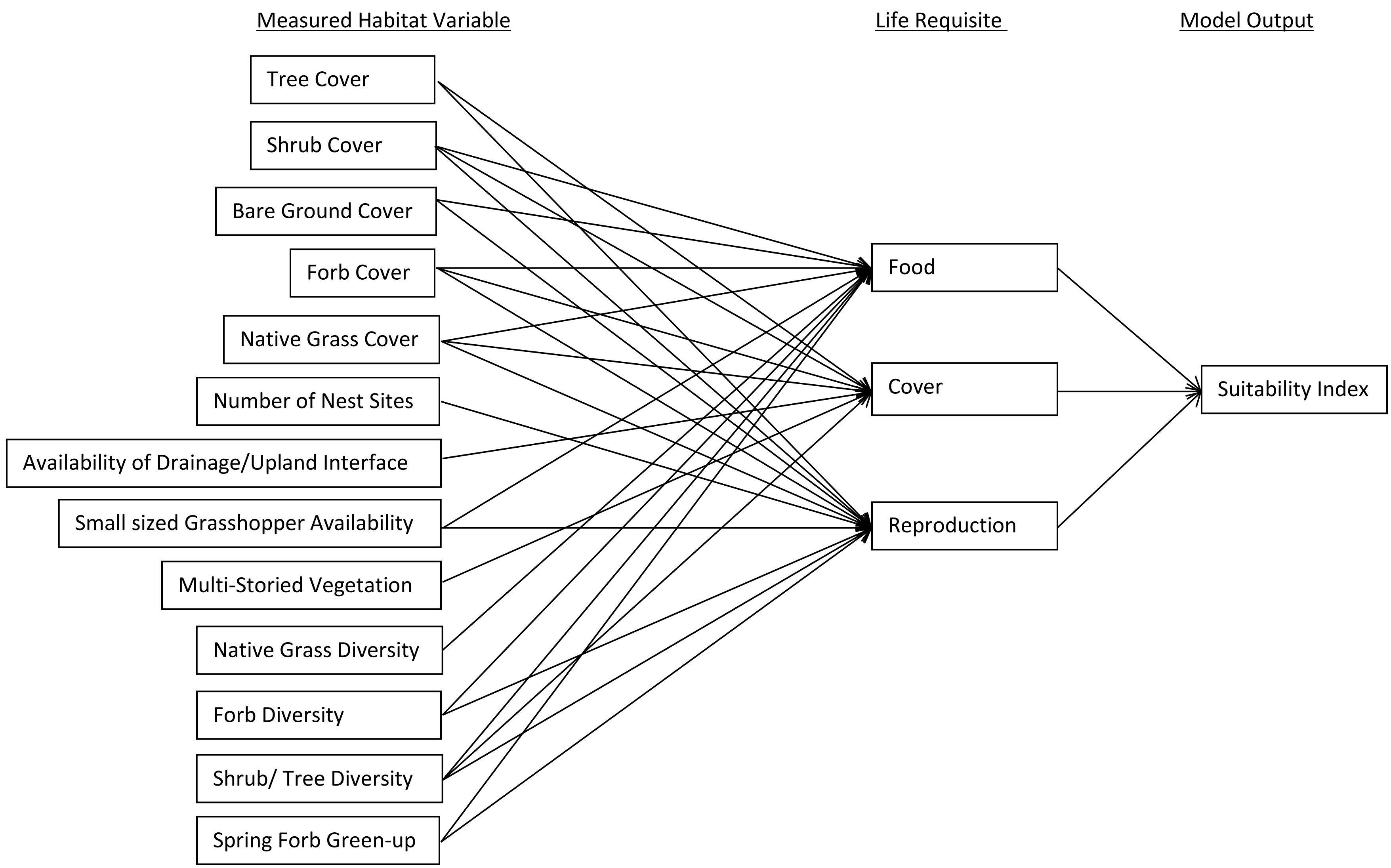
Bare ground is also important for reproduction. A very high amount of bare ground in needed for broods to be able to navigate and find food. The forb/grass cover can coalesce at the top, providing protection from predators, while being open underneath to allow chicks to move around and locate insects, sprouts, or seeds.

Mid-story shrub cover is essential in breeding areas to provide cover from predators and calling sites for males. As described above, these shrubs should be leguminous so that they can also serve as important sources of food later in the year.

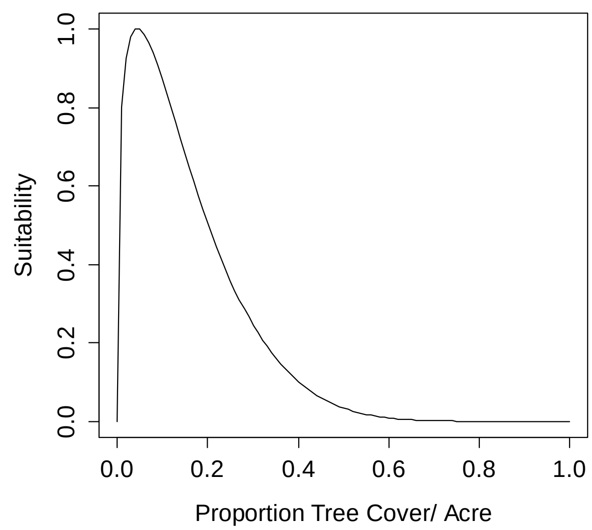
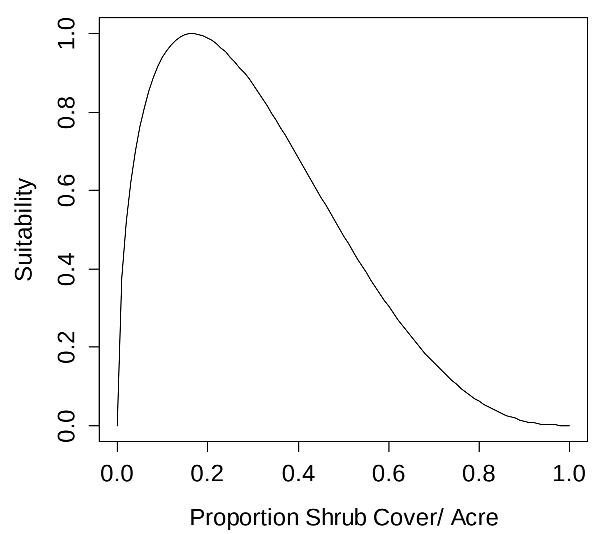
Spring green-up of vegetation is essential to reproduction in masked bobwhite and in quail in general. Adequate winter rain must exist for forbs and grasses to sprout. Without suppression of phytoestrogens present in drying vegetation the birds do not come into breeding condition. Green plants available for food in the spring promote normal reproduction.

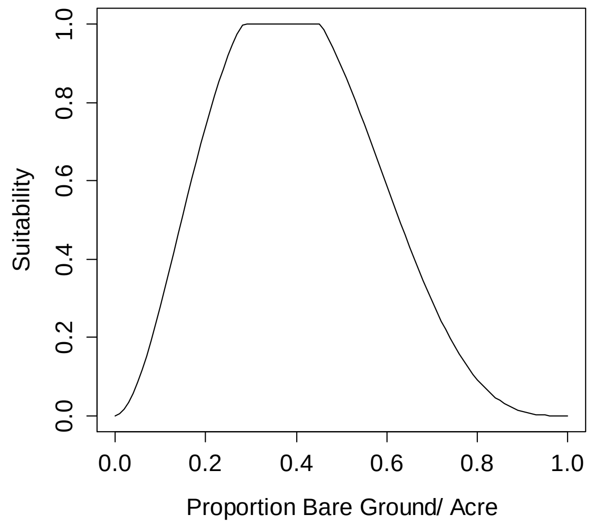
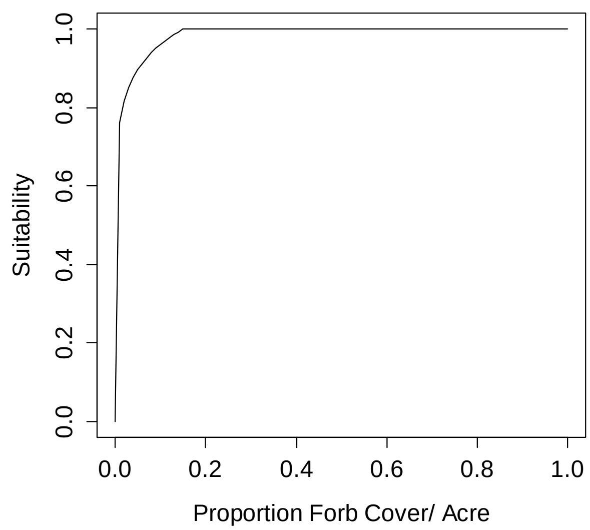
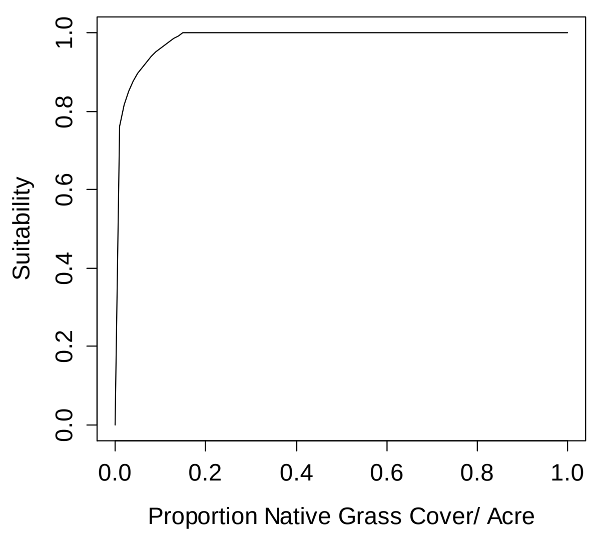
Section 3. Graphical Representation

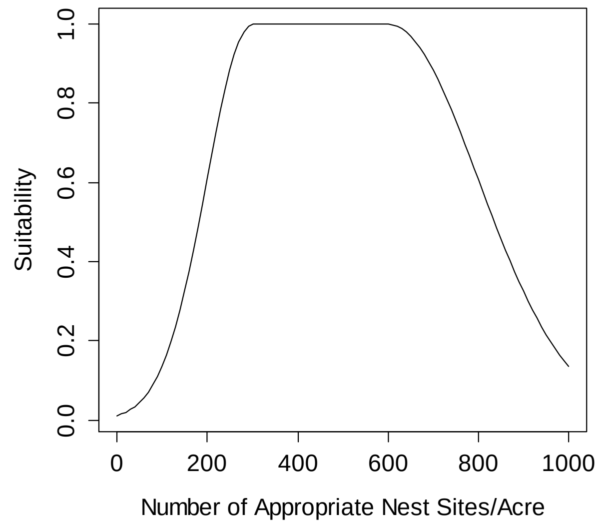
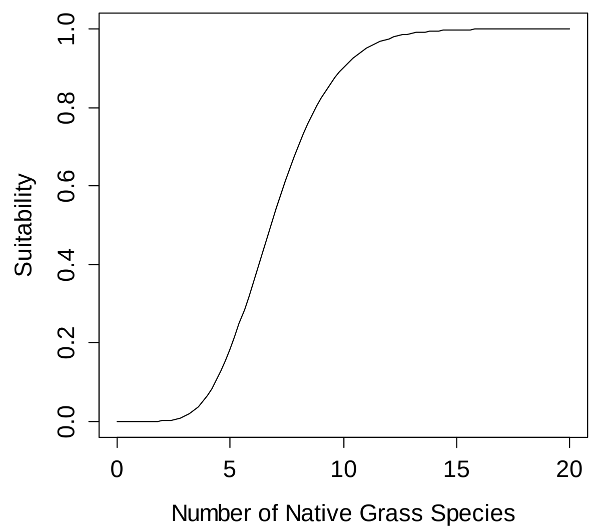
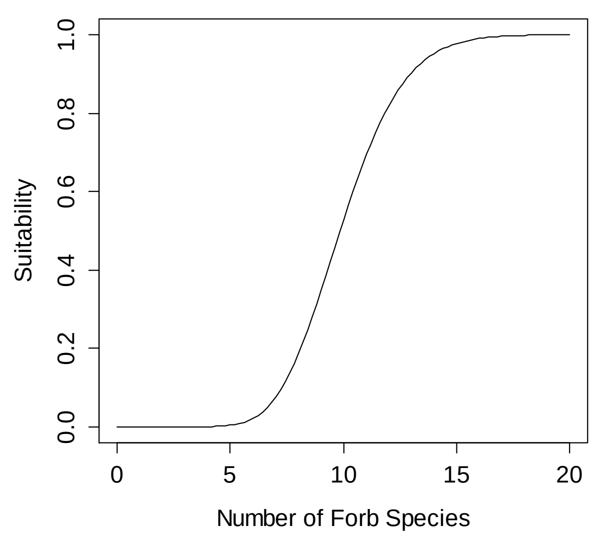
Figure 1. The relationship between measured habitat variables, critical life history requirements, and habitat suitability for masked bobwhites.

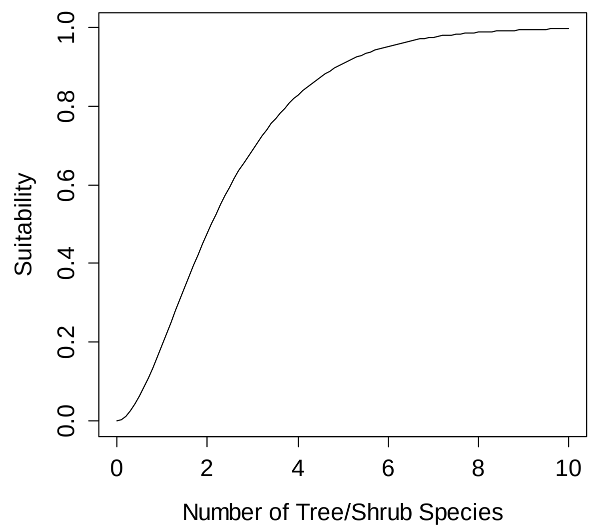
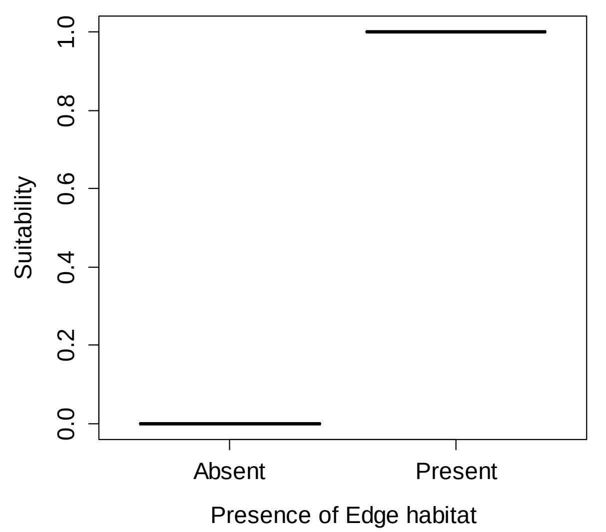
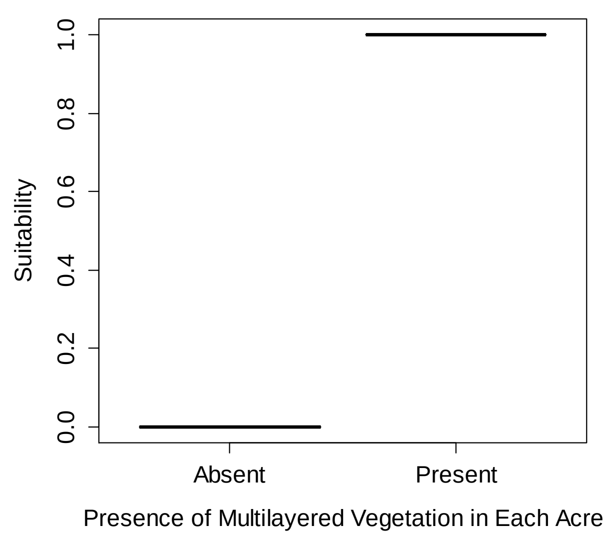


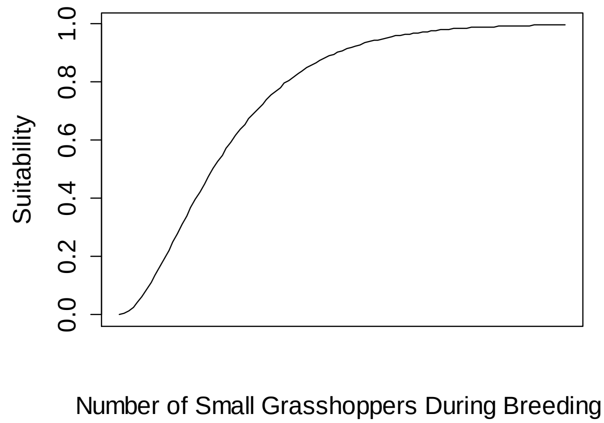
Section 4. Suitability Functions and Graphs

Variable	Description	Suitability Function	Suitability Graph
TC	Canopy Cover of trees as measured by a densitometer or aerial photo over each acre of ground.	$$F(x) = \frac{x^{0.3}(1-x)^{6.367}}{B(1.3,7.367)4.5}$$	
SC	Cover of woody shrubs as measured by aerial photo, or line intercept method, within each acre of ground.	$$F(x) = \frac{x^{0.5}(1-x)^{2.5}}{B(1.5,2.5)2.11}$$	

BG	Amount of bare ground, including that under vegetation. Must be capable of being traversed by a bobwhite. Measured as one would on Daubenmire transect.	$F(x) = \begin{cases} x < 0.28, \dfrac{x^2(1-x)^{3.5}}{B(3,4.5)2} \\ (.28 < x < .45), 1 \\ x > .45, \dfrac{x^2(1-x)^{3.5}}{B(3,4.5)2} \end{cases}$	
FC	Proportion of green forbs measured as one would in a Daubnenmire frame (per acre).	$F(x) = \begin{cases} x < .15, \dfrac{1.099x^{0.1}}{B(1.1,1)} \\ x > .15, 1 \end{cases}$	
GC	Proportion of native grass as measured by basal area by line intercept or Daubenmire Method (per acre).	$F(x) = \begin{cases} x < .15, \dfrac{x^{0.1}}{B(1.1,1)} \\ x > .15, 1 \end{cases}$	

NC	The number of appropriate nest sites, as counted in a frame or intercept technique, per acre.	$F(x) = \begin{cases} x < 300, \\ 250.6628\dfrac{exp\left\{-\dfrac{(x-300)^2}{2*100^2}\right\}}{\sqrt{2\pi 100^2}} \\ 300 < x > 600, 1 \\ x > 600, \\ 501.3257\dfrac{exp\left\{-\dfrac{(x-300)^2}{2*100^2}\right\}}{\sqrt{2\pi 100^2}} \end{cases}$	
GD	The number of native grass species per acre as counted on a line intercept	$F(x) = \dfrac{\int_0^{\frac{x}{1.4}} t^9 e^{-t} dt}{\Gamma(10)}$	
FD	The number of forb species per acre, as measured on a line intercept or frame method.	$F(x) = \dfrac{\int_0^{\frac{x}{2}} t^{19} e^{-t} dt}{\Gamma(20)}$	

SD	The number of shrub and tree species, per acre, as counted on a line transect or quadrant.	$F(x) = \frac{\int_0^{\frac{5x}{4}} te^{-t}dt}{\Gamma(2)}$	
EH	Presence or absence of an ecotone between drainage and upland grass habitat on each acre.	$F(x) = \begin{cases} 1 \; if \; Present \\ 0 \; if \; Absent \end{cases}$	
LV	The presence or absence of multi-layered vegetation on each acre.	$F(x) = \begin{cases} 1 \; if \; Present \\ 0 \; if \; Absent \end{cases}$	

GR	Grasshopper abundance during the breeding season on each acre. The exact relationship is unknown but more is better. The given function will assign suitability to an area relative to other measured areas.	$$F(x) = \frac{Rank(x)^2}{Length(x)}$$	

Equations.

The final habitat suitability index score is a result of the combination of suitability scores from component variables. The equations which describe this combination are governed by the assumptions and relationships described in section 2.2. Additive equations imply each variable in the equation can compensate for other variables with low scores unless otherwise noted. Multiplication implies a score of zero for any variable results in a suitability score equal to zero (i.e. both variables must have non-zero scores for the habitat to be suitable).

$$Food = \frac{SC + BG + FC + GC + GR + GD + FD + SD + GU}{9}$$

$$Cover = \frac{TC + SC + FC + GC + EH + LV + SD}{7}$$

$$Reproduction = \frac{TC + BG + SC + NC + FC + GC + GR + FD + SD + GU}{10}$$

$$HSI = Lowest\ score\ from\ Food, Cover\ or\ Reproduction$$

Habitat Suitability Index Model: Sally Gall and Dan Cohan

The following habitat suitability index model is the result of information obtained from the consensus of two species experts. Aspects of the model for which the experts failed to reach a consensus are identified as such. We developed this model following the U.S. Fish and Wildlife Service guide to the development of habitat suitability index (HSI) models 103-ESM (USFWS 1981). However, unlike typical HSI models, this model is intended to be used in conjunction with alternative HSI models developed from additional experts and existing literature. This model represents the best estimates of two species experts.

1. Model Applicability:

1.1 Geographic area. This model was developed based on knowledge of masked bobwhite habitat in both Arizona, specifically Buenos Aires National Wildlife Refuge, and northern Mexico.

1.2 Season. This model was developed to evaluate habitat needs of masked bobwhites over the entire year. The suitability of certain variables differs among seasons and these differences are noted and described in the model.

2. Model Description:

2.1 Overview. This model considers the ability of assessed habitat to meet the food, reproductive, and cover requirements of masked bobwhite as an indicator of overall habitat suitability. All components of the model are assessed by vegetative conditions. The relationship between habitat variables and critical life history requirements of masked bobwhite is illustrated in Figure 1.

2.2 Written Documentation.

The following sections provide a written documentation of the logic and assumptions used to interpret the habitat information for masked bobwhite in order to explain the variables and equations that are used in the HSI model. We present each critical habitat requirement and describe the variables which contribute to it.

1. Reproduction. Available habitat for masked bobwhites must contain adequate cover for nesting and brooding. Perennial bunch grasses of 1-2 feet (.3-.61m) in height are necessary for nesting substrate. Tree cover provides important perches for calling. Optimal values of tree cover are described under “Cover”. Structural diversity is important for providing the appropriate mix of nesting and brooding habitat. If all other cover components are at optimal levels, structural diversity is assumed to be optimal as well.
2. Food. Forb cover is an important source of food for both adults and juveniles. Masked bobwhites use forb foliage directly and indirectly by eating the insects which are associated with forbs. Optimal canopy cover of forbs is approximately 50% from the late summer through the winter whereas the optimum ranges from 35% to 65% in the spring and early summer. Forbs should be 0—6 inches tall to be directly utilized as food. Forb diversity is important for food during all months of the year, primarily because a diverse forb community will result in a diverse insect community. Forbs are also used directly as a food source early in the summer and forb height should be lower during that time to allow for access to the foliage by masked bobwhites. Food-bearing shrubs are an important source of food in the winter when other sources of food are scarce. Structural diversity is important year-round for food. High structural diversity

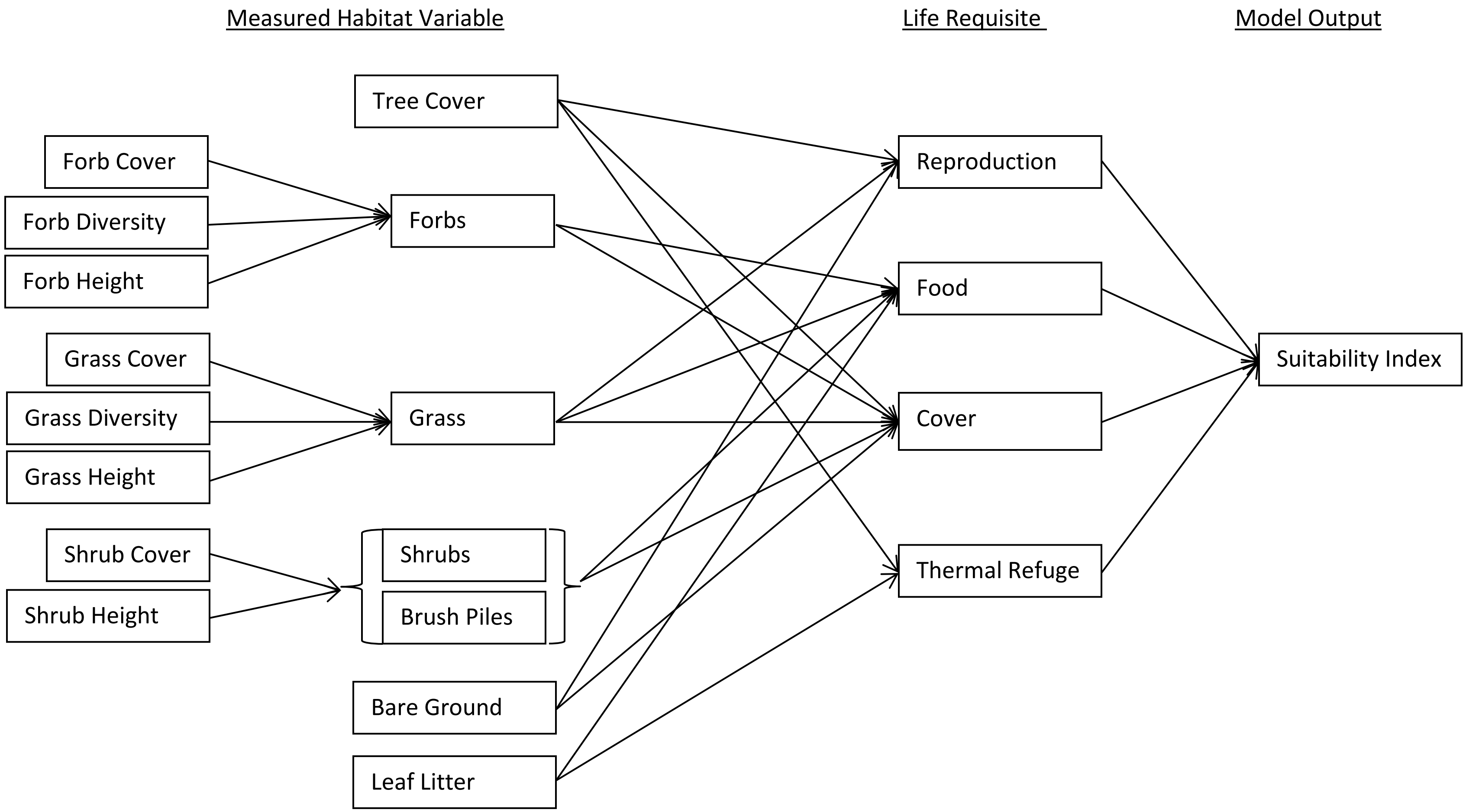
creates a wide array of micro-habitats which increases species richness of insect prey and diversity of herbaceous plants. Woodland-grassland edges improve habitat quality by providing a greater variety of options for food within a relatively small area. Leaf litter can provide additional food by improving insect abundance.

3. Cover. The height of forbs in the fall and winter should be at least 6 inches (15.24 cm) tall but forbs taller than 20 inches (50.8cm) are optimal to provide adequate cover. Forbs provide cover for masked bobwhites with optimal values for percent cover described above under "Food". Shrubs are also an important component of cover. Optimal values of shrub canopy cover differed between the two experts. Both experts stated optimal cover should be 10-60%; however one expert stated any value between these two would be optimal whereas the other expert believed that 40% cover is the optimal value with diminishing suitability above and below 40%. Both experts agreed that shrubs should be between 2 and 5 feet (0.91 and 1.5 m) tall with an optimal height of 4 feet (1.22m). Brush piles can substitute for shrubs when shrub cover is suboptimal. Brush piles should be approximately 50 feet (15.24 m) in diameter and 50 yards (46 m) apart, however, these figures can vary without affecting suitability. Brush piles should be low (<6 feet tall, <1.8 m tall) and dense. Brush piles should be placed in areas lacking natural cover, near natural cover and in uplands to provide additional cover during breeding. Perennial bunch grasses are important year round for cover. Optimal canopy cover of perennial grasses is 55%. Annual grasses also provide an important cover for masked bobwhite in the summer and fall with an optimal canopy cover of 45%. The proportion of perennial grasses to annual grasses should be approximately 80:20. The optimal height of grasses differed between the two experts. One expert stated optimal grass height is 4-5 feet (1.22-1.5m) tall whereas the other

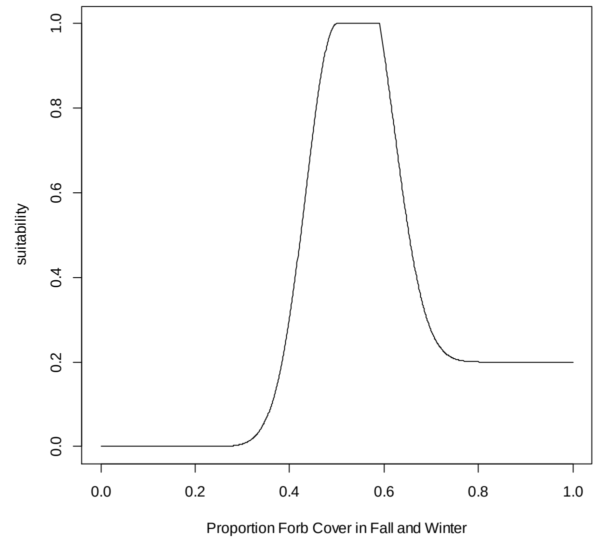
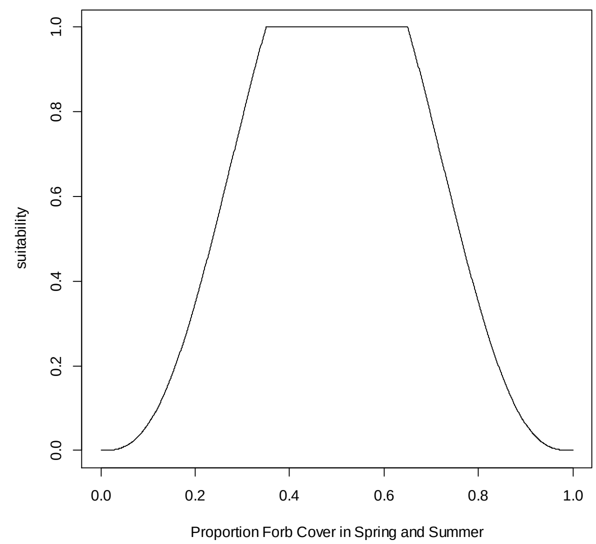
expert stated optimal grass height is 2-5 feet (.61-1.5m) tall. Trees are used as cover and provide structural complexity. Low tree cover is optimal (5% of canopy cover in the uplands and 30% in arroyos). Small trees can provide suitable cover in the absence of shrubs. Structural diversity is important during all months of the year and helps ensure adequate cover. Woodland-grassland edges provide a greater variety of options for cover within a small area. Bare ground is important during all seasons of the year for mobility of masked bobwhite but is most important in the fall to provide escape corridors after chicks begin to disperse. Areas with 25% bare ground are optimal.

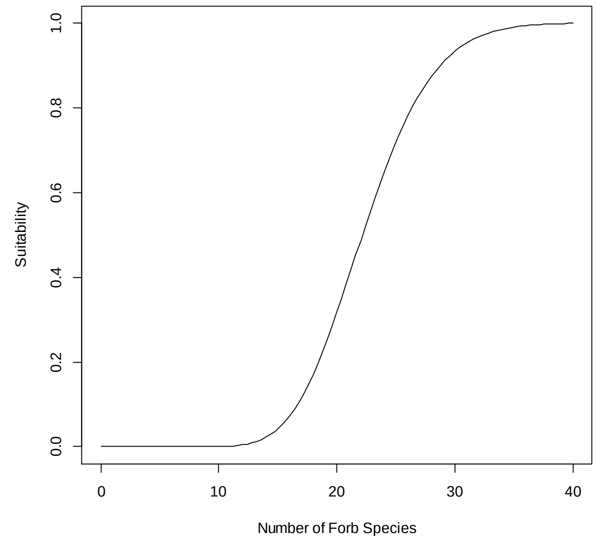
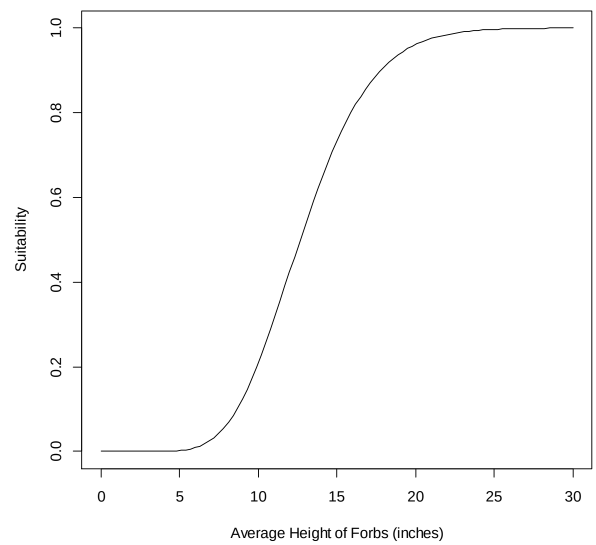
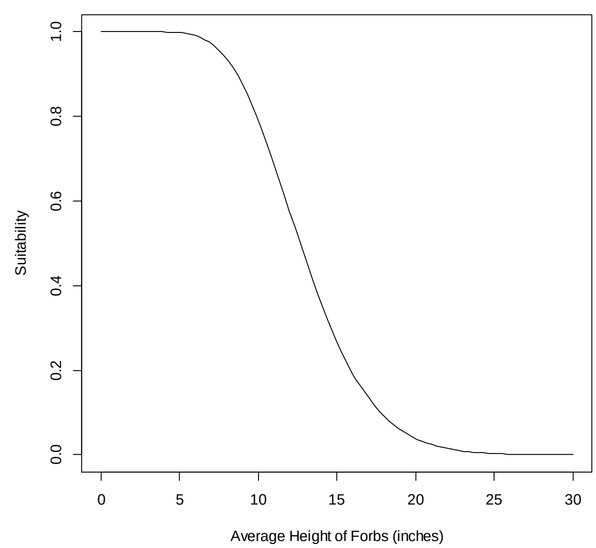
4. Thermal Refuge. Tree cover and shrub cover provides an important source of shade and perch sites for thermoregulation of masked bobwhites. Leaf litter is also important for thermoregulation by retaining moisture.

Figure 1. The relationship between measured habitat variables, critical life history requirements, and habitat suitability for masked bobwhites.



3. Suitability Functions and Graphs

Variable	Description	Suitability Function	Suitability Graph
FC	Forb cover measured as the average percent canopy cover dominated by forbs. The optimal canopy cover of forbs differs between the fall/winter and spring/summer.	Late Summer/Fall/Winter: $F(x) = \begin{cases} \frac{x^{29}(1-x)^{29}}{B(30,30)6.15}, x \leq .5 \\ 1, \quad .5 < x < .6 \\ 0.2 + \frac{x^{29}(1-x)^{23.5}}{B(30,24.5)6.3}, x \geq .6 \end{cases}$	
		Spring/ Summer: $F(x) = \begin{cases} \frac{x^{3}(1-x)^{3}}{B(4,4)1.65}, & x \leq .35 \\ 1, & .35 < x < .65 \\ \frac{x^{3}(1-x)^{3}}{B(4,4)1.65}, & x \geq .6 \end{cases}$	

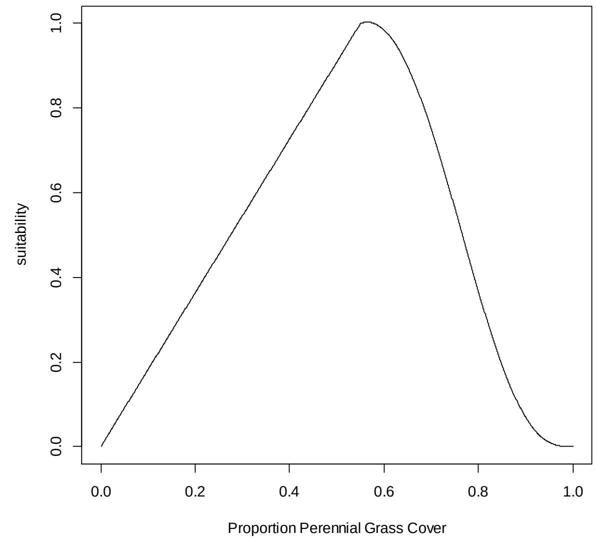
FD	Forb Diversity measured as the total number of forb species on a typical home range (10.9 ha) throughout the year.	$$F(x) = \frac{\int_0^x t^{21.5} e^{-t} dt}{\Gamma(22.5)}$$ (Gamma CDF with α=22.5, β=1)	
FH	Forb height measured as the average height of forbs. Optimal forb height differs between the spring/summer and the fall/winter.	<u>Fall/ Winter:</u> $$F(x) = \frac{\int_0^x t^{12} e^{-t} dt}{\Gamma(13)}$$ (Gamma CDF with α=13, β=1)	
		<u>Spring/ Summer:</u> $$F(x) = -\frac{\int_0^x t^{12} e^{-t} dt}{\Gamma(13)} + 1$$ (Gamma CDF with α=13, β=1)	

GC

Grass cover measured as the percent canopy cover of grass. The optimal canopy cover of grass differs between perennial and annual grasses.

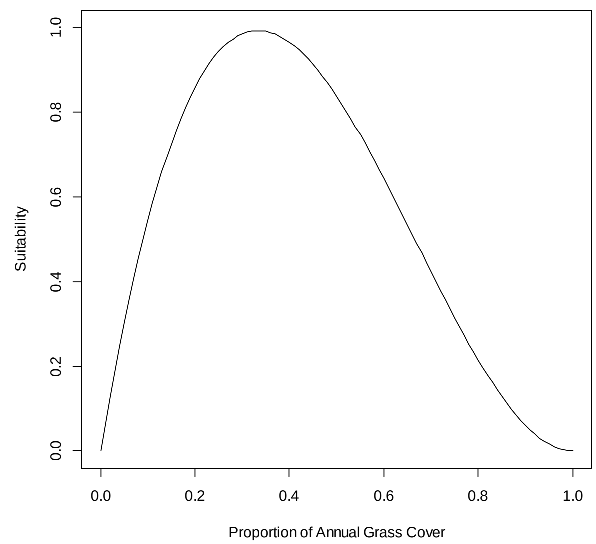
Perennials:

$$F(x) = \begin{cases} 1.82x, x \leq .55 \\ \dfrac{x^4(1-x)^{3.09}}{B(5,4.09)2.35} \end{cases}$$



Annuals:

$$F(x) = \begin{cases} \dfrac{x^1(1-x)^2}{B(2,3)1.79} \end{cases}$$



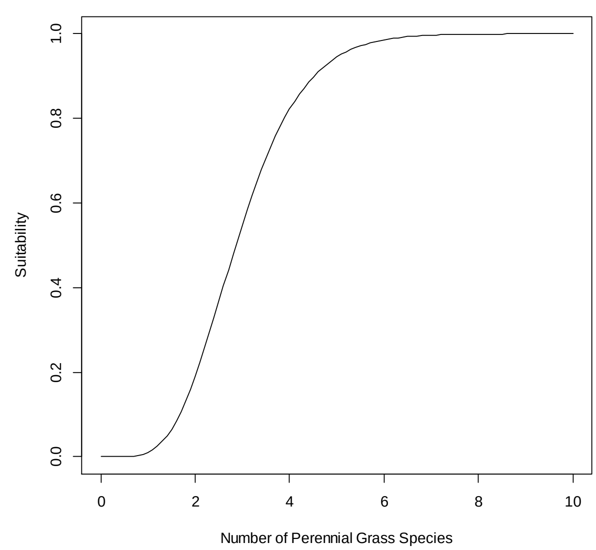
GD

Grass diversity measured as the total number of grass species found on a typical home range (10.9 ha). The optimal number of species differs between perennial and annual grasses.

Perennials:

$$F(x) = \frac{\int_0^{x/2.33} t^6 e^{-t} dt}{\Gamma(7)}$$

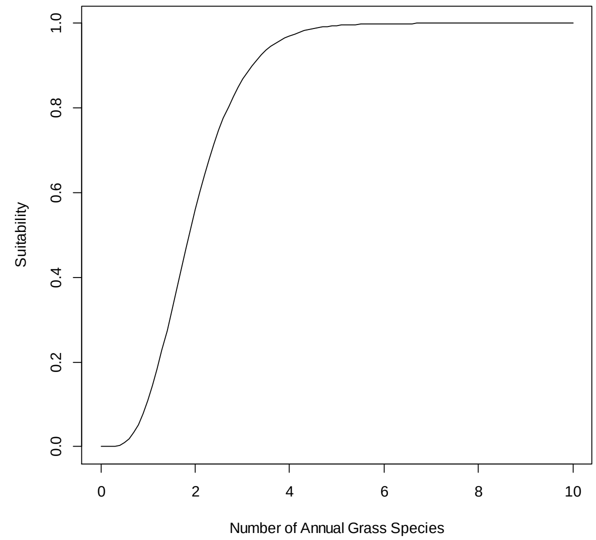
(Gamma CDF with α=7, β=2.33)



Annals:

$$F(x) = \frac{\int_0^{x/2.5} t^4 e^{-t} dt}{\Gamma(5)}$$

(Gamma CDF with α=5, β=2.5)

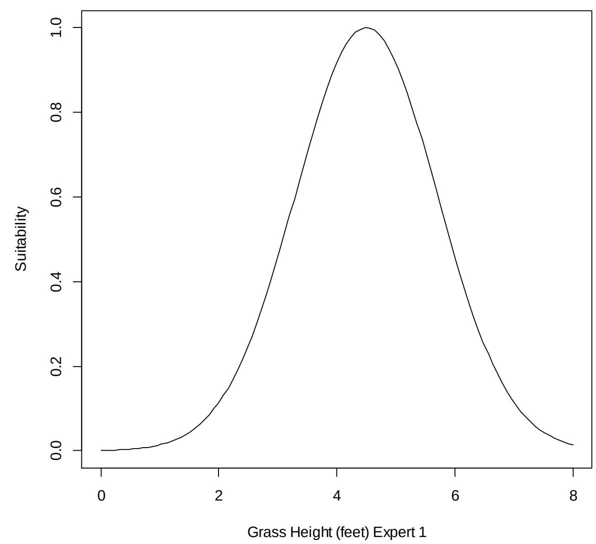


GH

Grass height measured as the average height of grass on a typical home range (10.9 ha). The two experts differed on their assessment of optimal grass height.

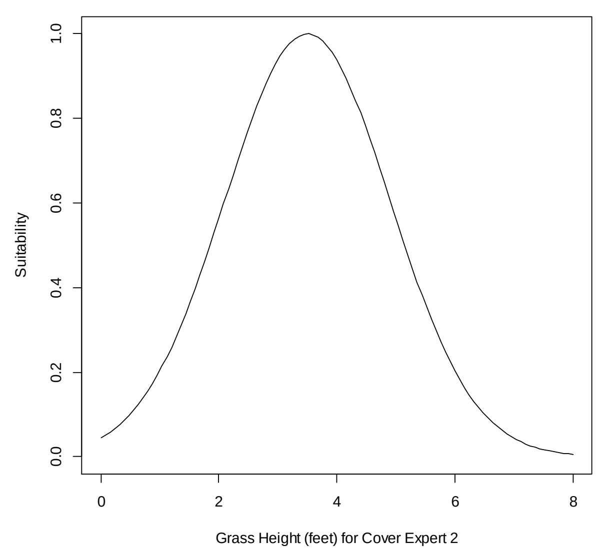
Expert 1:

$$F(x) = 3.01 \frac{e^{\frac{-(x-4.5)^2}{2.4}}}{\sqrt{2.4\pi}}$$



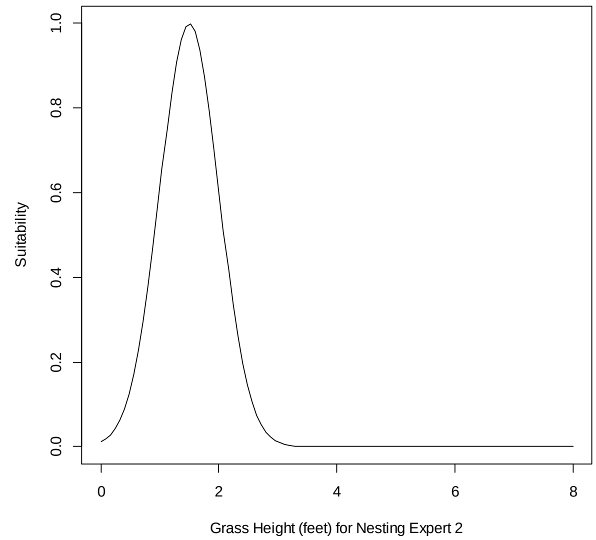
Expert 2 Cover:

$$F(x) = 3.51 \frac{e^{\frac{-(x-3.5)^2}{2.8}}}{\sqrt{2.8\pi}}$$



Expert 2 Nesting:

$$F(x) = 1.25\frac{e^{-(x-1.5)^2}}{\sqrt{\pi}}$$

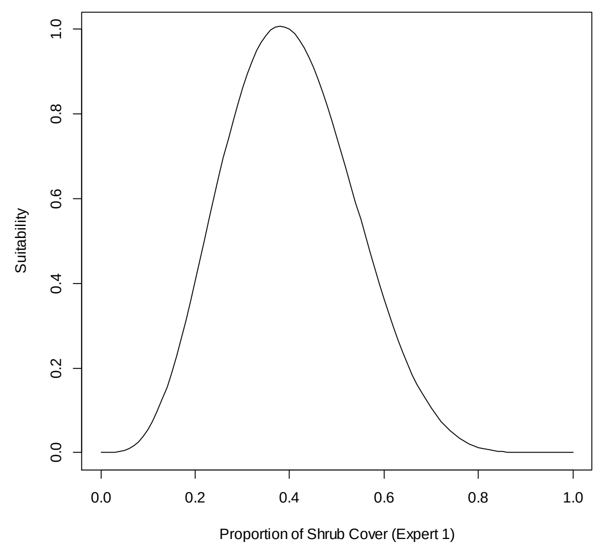


SC

Shrub cover measured as the average canopy cover of shrubs. The two experts differed in their assessment of optimal shrub cover.

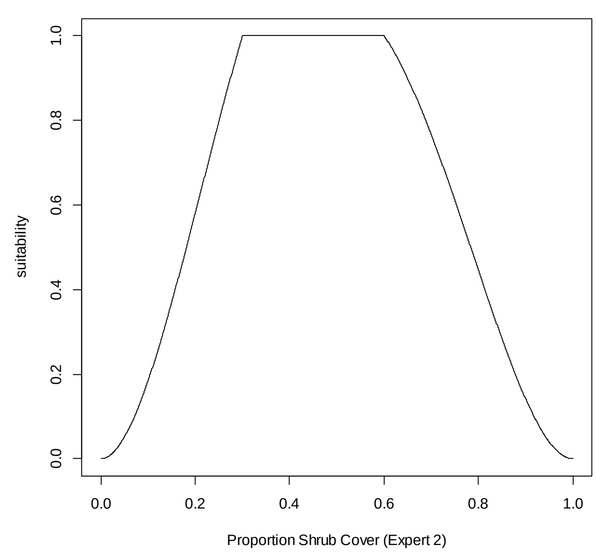
Expert 1:

$$F(x) = \frac{x^4(1-x)^{6.5}}{B(5,7.5)}$$



Expert 2:

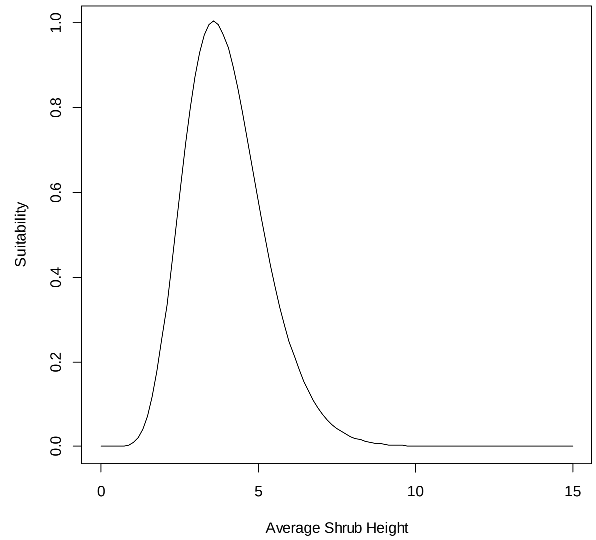
$$F(x) = \begin{cases} \dfrac{x^2(1-x)^2}{B(3,3)1.32}, & x \le .3 \\ 1, & .3 < x < .6 \\ \dfrac{x^2(1-x)^2}{B(3,3)1.73}, & x \ge .6 \end{cases}$$



SH

Shrub height measured as the average height of shrubs.

$$F(x) = \frac{3.05x^9 e^{-x/2.5}}{\Gamma(10)2.5^{10}}$$

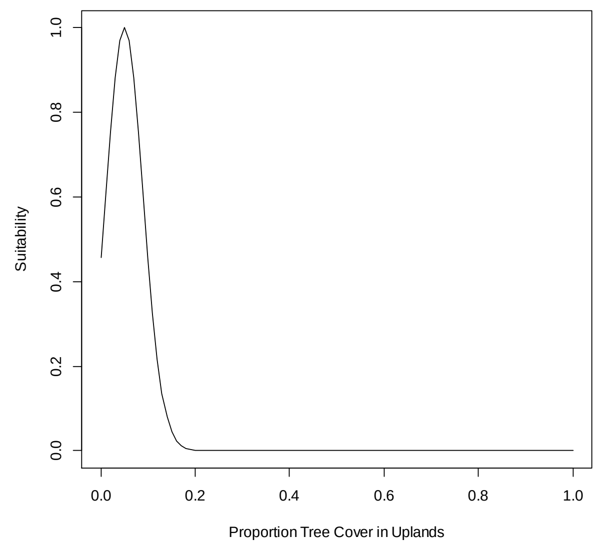


TC

Tree cover measured as the average canopy cover of trees. The optimal value of tree cover differs between the uplands and arroyos.

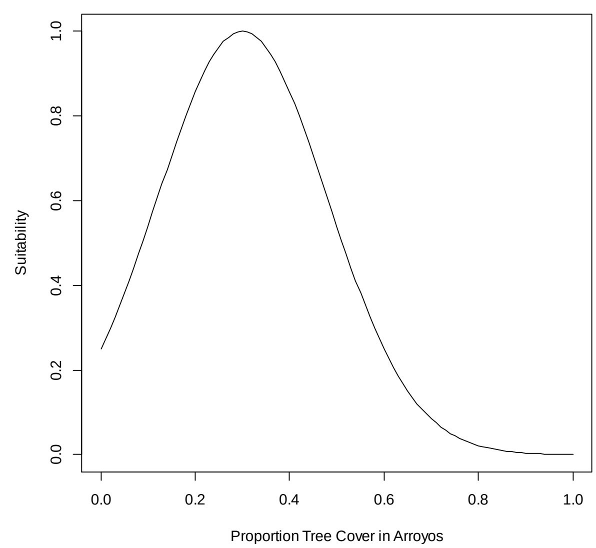
<u>Uplands:</u>

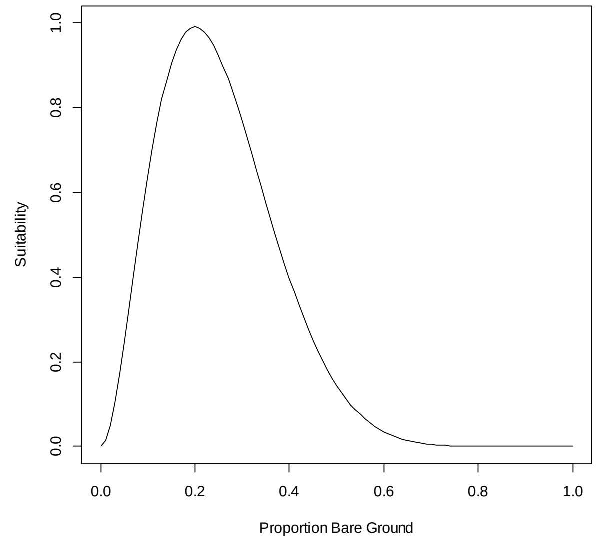
$$F(x) = 9.97\frac{e^{\frac{-(x-0.05)^2}{0.08}}}{\sqrt{0.08\pi}}$$



<u>Arroyos:</u>

$$F(x) = 2.22\frac{e^{\frac{-(x-0.3)^2}{0.26}}}{\sqrt{0.26\pi}}$$



BG	Bare ground measured as the average canopy cover of bare ground. Bare ground should be in the form of a matrix interspersed with other canopy components	$$F(x) = \frac{x^2(1-x)^8}{B(3,9)3.35}$$	

Equations.

The final habitat suitability index score is a result of the combination of suitability scores from component variables. The equations which describe this combination are governed by the assumptions and relationships described in section 2.2. Additive equations imply each variable in the equation can compensate for other variables with low scores unless otherwise noted. Multiplication implies a score of zero for any variable results in a suitability score equal to zero (i.e. both variables must have non-zero scores for the habitat to be suitable).

$$Forbs\ (F) = (FC * FD * FH)^{1/3}$$

$$Grass\ (G) = (GC * GD * GH)^{1/3}$$

$$Shrubs\ (S) = (SC * SH)^{1/2}$$

$$Reproduction = \frac{TC + G + BG}{3}$$

$$Food = \frac{F + G + S}{3}$$

$$Cover = \frac{TC + G + F + S + BG}{5}$$

$$Thermal\ Refuge = TC$$

$$HSI = Lowest\ score\ from\ Reproduction, Food, Cover\ or\ Thermal\ Refuge$$

Habitat Suitability Index Model: Roy Tomlinson

The following habitat suitability index model is the result of information obtained from a single species expert. We developed this model following the U.S. Fish and Wildlife Service guide to the development of habitat suitability index (HSI) models 103-ESM (USFWS 1981). Unlike typical HSI models, this model is intended to be used in conjunction with alternative HSI models developed from additional experts and existing literature. This model represents the best estimates based on the expertise of one individual who is a recognized expert on the Masked Bobwhite.

<u>1.Model Applicability</u>:

<u>1.1 Geographic area</u>. This model was developed based on knowledge of masked bobwhite habitat in Mexico.

<u>1.2 Season.</u> This model was developed to evaluate habitat needs of masked bobwhites over the entire year.

<u>2. Model Description:</u>

<u>2.1 Overview.</u> This model considers the ability of assessed habitat to meet the food, reproductive, and cover requirements of masked bobwhite as an indicator of overall habitat suitability. All components of the model are assessed by vegetative conditions. The relationship between habitat variables and critical life history requirements of masked bobwhite is illustrated in Figure 1.

<u>2.2 Written Documentation.</u>

The following sections provide a written documentation of the logic and assumptions used to interpret the habitat information for masked bobwhite in order to explain the variables and equations that are used in the HSI model. We present each critical habitat requirement and describe the variables which contribute to it.

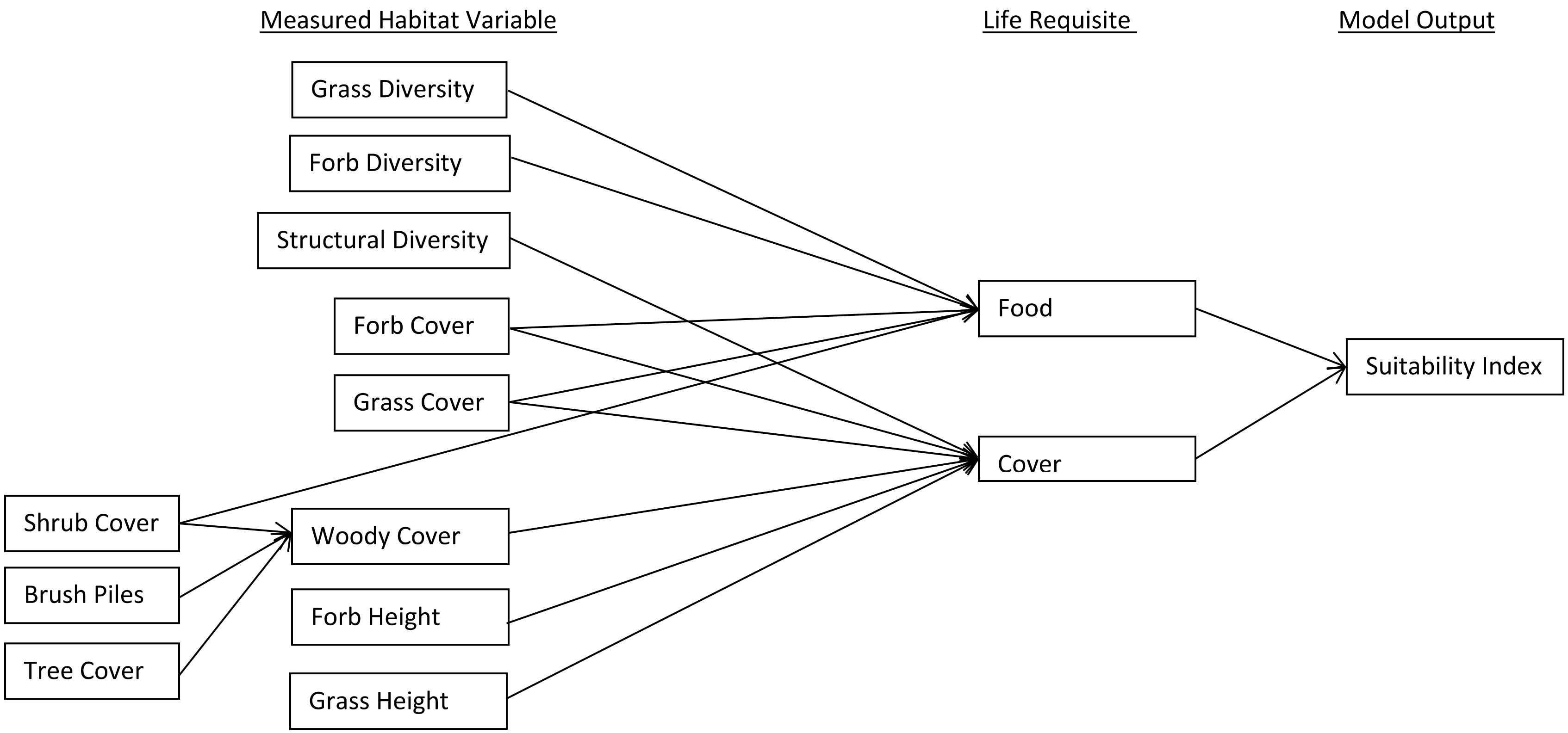
4. Reproduction. Habitat is assumed to be suitable for reproduction if both food and cover are suitable.
5. Food. Forb diversity is important year round because forbs are a source of food. In the winter and early spring, when food is scarce, forb seeds are critical. Forbs are consumed directly as forage in the summer and fall. Habitat suitability increases with increasing forb diversity. Likewise, grasses are also an important source of food. Leguminous shrubs, such as *Acacia angustissima,* provide a source of food in the winter months when other sources of food are scarce. Abundance of a variety of grass species (high grass diversity) provides an important source of food for masked bobwhite. Insects, e.g. grasshoppers, provide necessary protein for immature masked bobwhite growth during summer and fall. They may also play a small role in the diet of adults.
6. Cover. Masked bobwhites have different habitat requirements in the winter and summer. In the summer, masked bobwhites prefer more open areas with primarily grass and forb cover. In the winter, they prefer more closed areas with a mix of small trees and shrubs. Therefore, the optimal canopy cover of forbs, grass, shrubs, and trees differs between winter and summer. In the summer, optimal habitat includes areas with approximately 50 percent coverage by grass, 30 percent coverage by forbs, 10-20 percent coverage by shrubs and small trees, and 25 percent coverage by bare ground defined as

unobstructed ground surface (coverage sums to >100 percent due to overlap of coverage). In the winter, optimal habitat includes areas with approximately 50 percent coverage by grass and forb (combined), 50-75 percent coverage by shrubs and small trees, and 25 percent coverage by bare ground (unobstructed ground surface). Grass cover should include primarily annuals such as Rothrock's, black, or side-oats grama (see species list in Appendix A). Both forb and grass cover should be measured as a stem density. Masked bobwhites need a balance between adequate overhead cover and adequate openings in the vegetation to move and to detect predators. Buffelgrass (*Pennisetum ciliare*) generally fails to meet this balance because it forms stands which are too dense (lack adequate openings). The explicit relationship between plant density (cover) and habitat suitability of masked bobwhite is not well-established. Shrub cover is an important component in the winter and spring when cover from grass and forbs is minimal. Beneficial shrub species are listed in appendix A. Creosote-dominated areas are considered poor habitat for masked bobwhite during all months of the year. Dense woody areas are only used as escape cover and, therefore, some dense woody vegetation must be available to masked bobwhites but it must only account for a small portion of the landscape. Optimal summer habitat differs from optimal winter habitat and so both must be present in an area (in relatively close proximity) so that habitat requirements are met in all months of the year. Moreover, optimal habitat includes areas where transitions (ecotones) between open areas and tree/brush areas are abrupt.

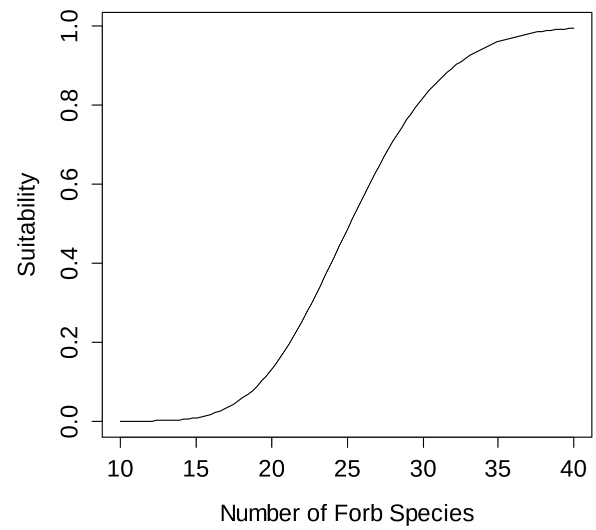
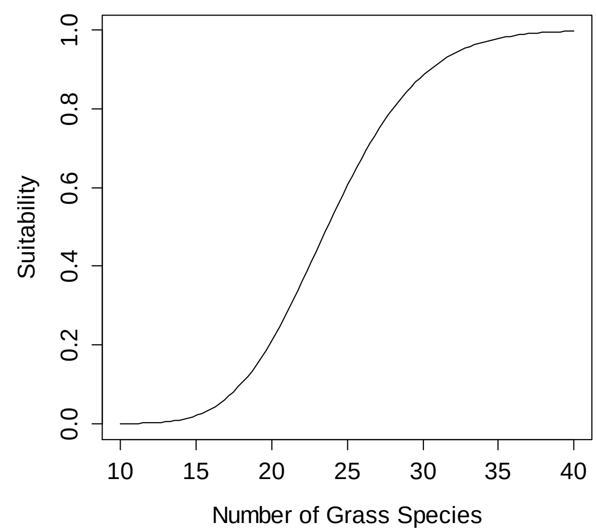
7. Weather – Masked bobwhites have singularly adapted to a weather pattern where the onset of breeding begins when the annual “monsoon” season begins (ca. July1). A “good” rainy season is characterized by frequent and relatively non-violent rainfall throughout the period (10-14 inches was considered optimal). This pattern allows the optimal growth and maturation of food-bearing plants and insects as well as grass and brush for cover. If the annual precipitation is delayed or significantly diminished, the chances of masked bobwhite breeding success are also diminished accordingly. Because the rainy season is so short (3 months), re-nesting after initial failure can be significantly reduced, whereas other quail (Gambel’s and Elegant) have much longer breeding seasons and therefore greater odds of re-nesting success.

8. Altitudinal Distribution – Masked bobwhites are limited in distribution by altitude; they generally have never been found in areas below 1,500 feet (asl) nor above 4,500 feet. Therefore, they never occupied the low, drier southwestern areas or the higher mountain areas of Sonora. This factor is probably related to habitat requirements not found in the more extreme altitudinal zones.

Figure 1. The relationship between measured habitat variables, critical life history requirements, and habitat suitability for masked bobwhites.



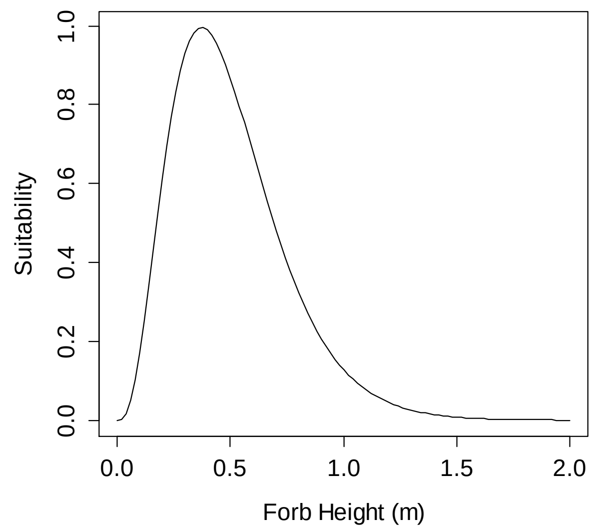
3. Suitability Functions and Graphs

Variable	Description	Suitability Function	Suitability Graph
FD	Forb Diversity measured as the total number of forb species on a typical home range (10.9 ha)	$F(x) = \frac{\int_0^x t^{24.5} e^{-t} dt}{\Gamma(24.5)}$ (Gamma CDF with α=25.5, β=1)	
GD	Grass Diversity measured as the total number of both annual and perennial grass species on a typical home range (10.9 ha)	$F(x) = \frac{\int_0^x t^{23} e^{-t} dt}{\Gamma(23)}$ (Gamma CDF with α=24, β=1)	

FH

Forb Height measured as the average height of forbs on a typical home range (10.9 ha)

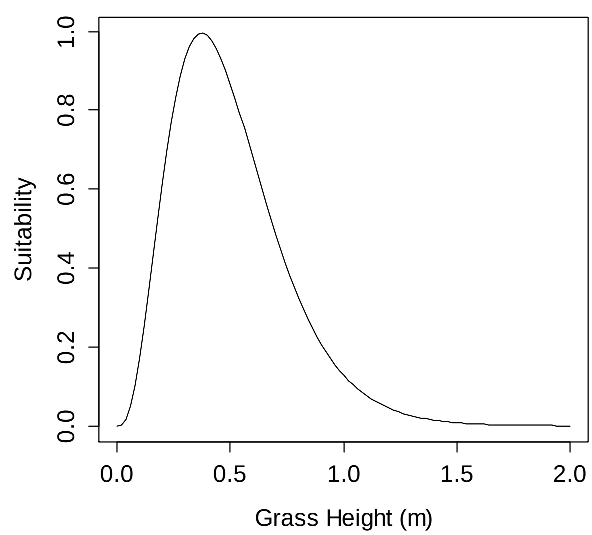
$$F(x) = \frac{x^3 e^{-x/8}}{\Gamma(4)8^4 * 1.8}$$



GH

Grass Height measured as the average height of grass on a typical home range (10.9 ha)

$$F(x) = \frac{x^3 e^{-x/8}}{\Gamma(4)8^4 * 1.8}$$

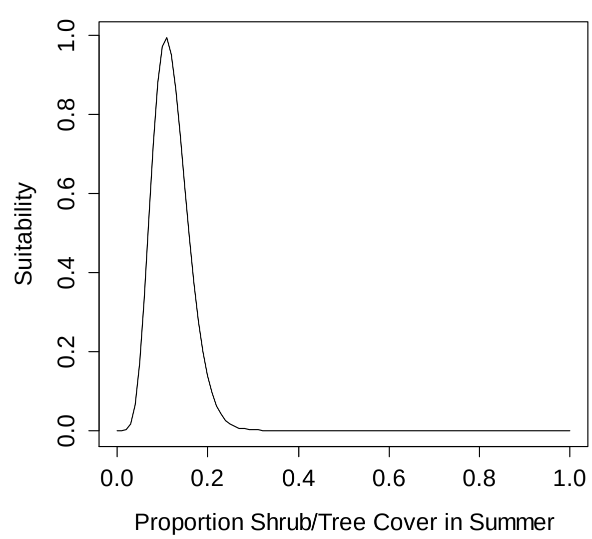


TCS

Tree and shrub cover measured as the percent canopy cover of trees on a typical home range (10.9 ha). Optimal tree and shrub cover differs between summer and winter. Brush piles can be incorporated to improve suitability.

<u>Summer</u>:

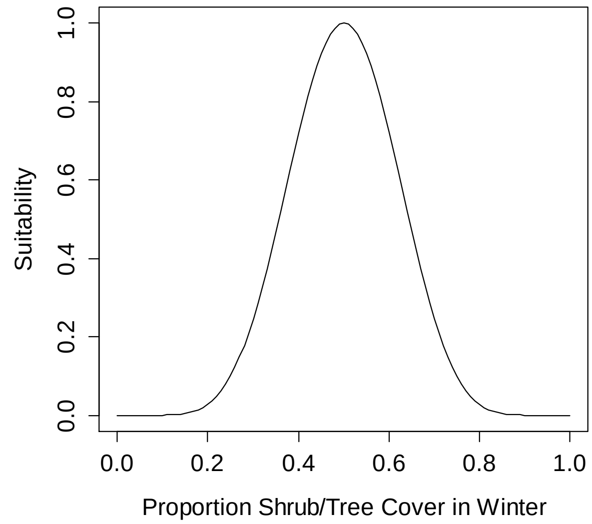
$$F(x) = \frac{x^7(1-x)^{57.67}}{B(8,58.67)10.4}$$



TCW

Winter:

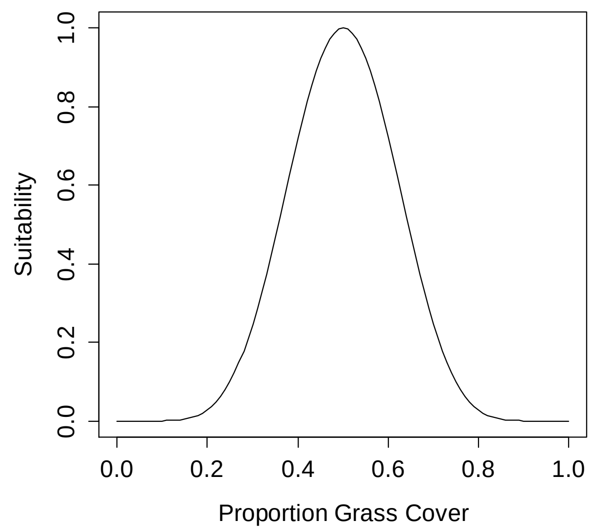
$$F(x) = \frac{x^8(1-x)^8}{B(9,9)3.34}$$



GC

Grass Canopy Cover measured from above the grass canopy as the amount of ground covered by grass foliage on a typical home range (10.9 ha)

$$F(x) = \frac{x^8(1-x)^8}{B(9,9)3.34}$$

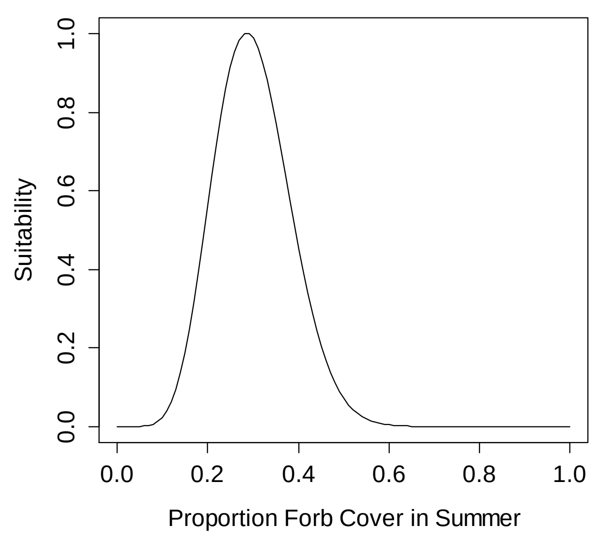


FCS

Forb Cover measured as the average total canopy cover of forbs on a on a typical home range (10.9 ha). Suitability of forb cover differs in winter and summer.

Summer:

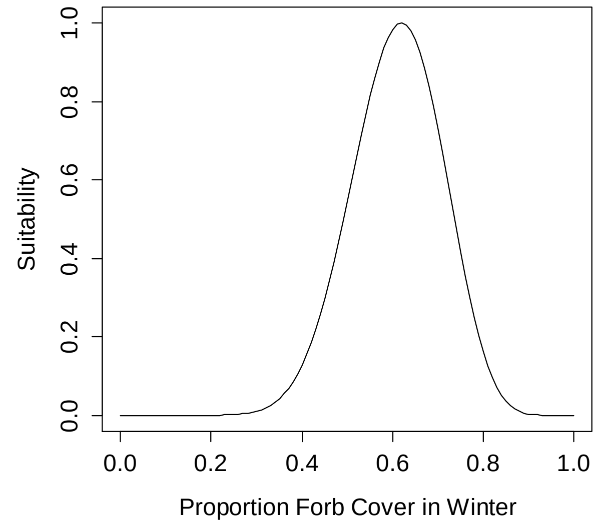
$$F(x) = \frac{x^8(1-x)^{20}}{B(9,21)4.778}$$



FCW

Winter:

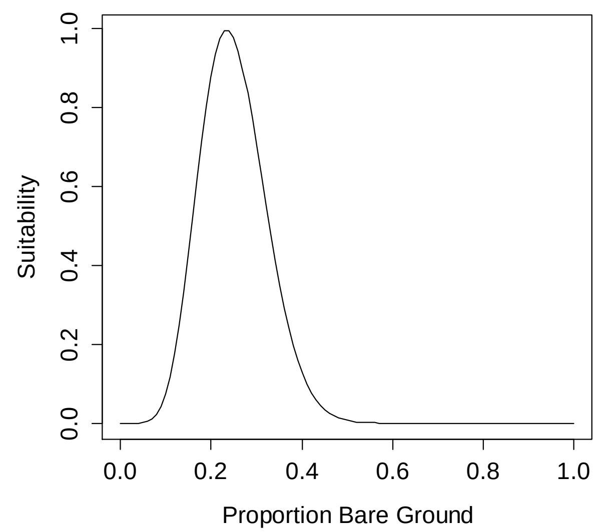
$$F(x) = \frac{x^{13}(1-x)^{8}}{B(14,9)3.34}$$



BG

Bare Ground measured as the proportion of surface area not occupied by stems or other obstructions on a typical home range (10.9 ha).

$$F(x) = \frac{x^{8}(1-x)^{26}}{B(9,27)5.6}$$



Equations.

The final habitat suitability index score is a result of the combination of suitability scores from component variables. The equations which describe this combination are governed by the assumptions and relationships described in section 2.2. Additive equations imply each variable in the equation can compensate for other variables with low scores unless otherwise noted. Multiplication implies a score of zero for any variable results in a suitability score equal to zero (i.e., both variables must have non-zero scores for the area to be habitat).

$$TC = \min(TCS, TCW)$$

$$FC = \min(FCS, FCW)$$

$$Food = \frac{((GD * GC)^{\frac{2}{5}} + (FD * FC)^{\frac{3}{5}})}{2}$$

$$Cover = \frac{FH + GH + FC + GC + TC}{5}$$

$$HSI = Lowest\ score\ from\ Food\ or\ Cover$$

Appendix A: List of Beneficial Plant Species

Grasses

- *Trichachne spp* – Arizona Cottontop
- *Bouteloua spp* – Gramma
    - *curtipendula* – side oats
    - *filiformis* – slender
    - *rothrockii* – rothrocks
    - *barbata* – six weeks
- *Cathesticum* spp
- *Chloris* spp
- *Tridews* spp
- *Eragrostis* spp – lovegrass (No Lehman's)
- *Andropogon*
- *Setaria macrostachya* – Bristle grass
- *Sorghum halepense* – Johnson grass
- *Panicum* – Panic grass
    - *obtusum* – Vine mesquite
    - *virgatum* – Switch grass
- *Sporobolus* – Dropseed
    - *airoides* – Alkali sacaton
    - *cryptandrus* – Sand dropseed
- *Echinochloa crus-galli* – Barnyard grass
- *Aristida spp* – Three awns

Forbs and Shrubs

- *Jatropha spp* – Sangre de Drago
- *Kallstroemia spp* – Arizona poppy
- *Gutierrezia spp* – Snake weed
- *Chalochortus kennedyi* – Desert mariposa
- *Rumex hymenosepalus*
- *Anionia spp* – Four-o-clock
- *Abronia spp* – Sand verbena
- *Eschscholzia californica spp* – Mexican gold poppy
- *Argemone spp* – Prickle poppy
- *Oenothera spp* – Evening primrose
- *Calliandra eriophylla* – False mesquite

- *Acacia greggii* – Catclaw acacia
- *Acacia angustissima* – Prairie acacia
- *Cassia spp* – Senna
- *Astragalus spp* – Locoweed
- *Sphaeralcea spp* – Desert mallow
- *Ferrocactus spp* – Barrel cactus
- *Opuntia spp* – Prickly pear
- *Cholla spp*- several species
- *Fouguieria spp*- Ocotillo
- *Phlox spp*
- *Phacelia spp* – Scorpion weed
- *Nama spp*
- *Datura spp*
- *Curcurbita spp* – Gourd

Overstory

- *Prosopis spp* – Mesquite
- *Olneya tesota* – Ironwood
- *Cercidium spp* – Palo verde
- *Carnegiea spp* – Saguaro

Habitat Suitability Index Model: Published Literature

The following is a habitat suitability model developed solely from published literature pertaining to the masked bobwhite (*Colinus virginianus ridgwayi*). The model is divided into five sections: 1) model applicability (where and when does this model apply), 2) a written description of the model and its parameters, 3) graphical models showing the relevant habitat variables and their relationship to life history requisites, 4) graphical representations of the relationships between habitat suitability and each habitat variable, and 5) a mathematical representation of the model.

Section 1.Model Applicability:

1.1 Geographic area. This model describes optimal habitat for masked bobwhites in northern Sonora, Mexico and southern Arizona, United States. The Rancho el Carrizo area of Sonora, Mexico was the primary location for data collection in Mexico.   In Arizona, this model describes optimal habitat for masked bobwhite within Buenos Aires National Wildlife Refuge (BANWR).

1.2 Season. This model describes optimal habitat for masked bobwhite during all times of the year but much of the literature is focused on habitat conditions during the summer and fall.

Section 2. Model Description:

2.1 Overview. The purpose of this model is to consider the ability of assessed habitat to meet the food, reproductive, and cover requirements of masked bobwhite as an indicator of overall habitat suitability.

2.2 Written Documentation.

The following section provides a written documentation of the logic and assumptions used to interpret the habitat information for masked bobwhite in order to explain the variables and equations that are used in the HSI model.

2.2.1 General Habitat Description

The suitability for masked bobwhites of a point in space (which is associated with a set of habitat components) may vary through time because different habitat components are required at different times (Guthery 1997, 1999). The goal of habitat management for masked bobwhites should be to maximize suitability of each point is space through time (Guthery et al. 2000, 2001). For a species that utilizes different habitat components at different times of the year, such as the masked bobwhite, quantifying optimal habitat can become a difficult and data-intensive process since habitat use (preference) needs to be measured at multiple times of the year. Unfortunately, very little empirical data exists for describing the habitat relationships of masked bobwhite and much (if not all) of the data was collected on populations which were in severe decline during the sampling period. Therefore, habitat suitability descriptions included in this document describe the best available habitat for masked bobwhites at the time of sampling and may not represent optimal habitat conditions for masked bobwhites.

The general habitat of masked bobwhites is described in the early literature, although these documents only provide very general habitat descriptions. Grinnell (1884) and Brown (1885) describe the general habitat as mesas, valleys, and possibly foothills but not canyons or mountains. This description was later echoed by Van Rossem (1945) and Monson and Phillips (1964) who described masked bobwhite habitat as "tall-grass mesquite plains." Ligon (1952) described masked bobwhite habitat as "deep-grass-weed" and Gallizioli et al. (1967) concluded that dense stands of perennial grasses are important. In his review of the early masked bobwhite literature, Tomlinson (1972) concluded that open grasslands with adjoining brushy areas at elevations between 305m and 1220m were preferred by masked bobwhites. Tomlinson (1972) also concluded that denser grasses, such as sacaton (*Sporobolus* spp.), are primarily used for hiding whereas associations of mixed grammas (*Bouteloua* spp.) and three-awns (*Aristida* spp.) are preferred for loafing and feeding.

Similarly, only limited information exists on the feeding habits of masked bobwhites from the early literature. The diet of masked bobwhite is composed of insects ranging in size from 1mm – 2.5cm, seeds, and vegetation (Brown 1885). Table 1 is excerpted from Tomlinson (1972) and summarizes the most common stomach contents from 10 masked bobwhites collected in Northern Sonora, Mexico in October 1931 (Cottam and Knappen 1939).

Table 1. The stomach contents of 10 masked bobwhites collected in Northern Sonora, Mexico, in October 1931 (from Tomlinson 1972).

Food Source	Number of Birds (of 10)	% of Total Food
Acacia angustissima	8	18.8
Physalis spp.	10	16.3
Panicum halli	8	12
Panicum stramineum	8	2.3
Panicum arizonicum	8	0.3
Miscellaneous Grasses		3.4
Commelina elegans	9	10.8
Phaseolus ritenesis	4	3.8
Abutilon cripsum	9	1.9
Abutilon incanum	9	1
Abutilon arizonicum	9	Trace
Cassia leptodena	6	2.5
Ipomoea spp.	5	2.3
Galactea spp.		2.2

Melanoplus spp. (grasshopper)	1	8.8
Romalea spp. (grasshopper)	3	7.1
Unknown Grasshopper	4	2.5
Unknown Orthoptera	4	.9
Miscellaneous Insect		1.6

2.2.2 Quantified Habitat Metrics

1. Cover-

Cover serves two important roles for masked bobwhites, protection from predators and thermal regulation. Masked bobwhites appear to alter their habitat preference during different periods of the year. These periods can be broken down into the fall and winter covey season, the spring pair formation season, and the summer breeding season. A quantitative analysis of optimal cover values was undertaken by Simms (1989), King (1998), and Guthery et al. (2000, 2001).

Karen Simms (1989) compared habitat conditions on core use areas to conditions on home ranges and representative transects within the Buenos Aires National Wildlife Refuge. She found that masked bobwhites generally selected bottomland grass and tree-shrub habitat. Simms found masked bobwhites preferred areas with higher aerial and basal cover of grass and greater visual obstruction from all vegetation at 0-10 cm. Simms also found masked bobwhites preferred lower percent cover of tree and shrub cover in core areas when compared to the entire home range. However, she also found that masked bobwhites preferred areas with higher density of trees between 0 and 5m tall and that small trees were favored over half-shrubs. Simms speculated that small trees provided better cover than dense half-shrub species which do not have adequate space under the crown for loafing, foraging, and hiding.

Nina M. King (1998) compared the vegetation at sites used by masked bobwhites to random sites located within the Buenos Aires National Wildlife Refuge. During the covey season, Nina found masked bobwhites preferred taller vegetation and greater vegetation biomass than found at random sites. King also found limited evidence that bobwhites preferred lower levels of herbaceous cover (32% cover selected vs 42% cover randomly available) and bare ground (11% cover selected vs 16% cover randomly available)and higher levels of woody stem density cover (47 stems/ 200 m^2 selected vs 42 stems/ 200 m^2 randomly available) than was typically available on the landscape. King found no preference related to woody cover, number of grasses , or grass and forb species richness during the covey season. King also found that quail were positively associated with Lehmann's lovegrass (*Eragrostis lehmanniana*), snakeweed (*Gutierrizia* spp.), and mesquite (*Prosopis* spp.). The positive association with non-native Lehmann's lovegrass may be a result of the relative persistence of this grass during dry periods (Kuvleski et al. 2002). During the pair formation/breeding season, King (1998) found bobwhites preferred greater woody canopy cover than was found at random sites. Bobwhites were also positively associated with a greater total amount of half-shrubs and tree species than found at random sites.

Overall, King (1998) found that bobwhites selected sites with greater structural diversity than was typically available and taller vegetation than was found at random sites. King also found that bobwhites selected sites with less bare ground, and therefore areas which were less patchy, than was randomly available. At release sites, King (1998) found that sites with greater total cover had higher survival rates for released bobwhites.

Guthery et al. (2000) compared the vegetative features at sites used by masked bobwhites to randomly selected sites in both Arizona and Sonora. They also compared these features to sites in Texas which were utilized by the related Texas bobwhite. The Arizona sites included in Guthery et al. (2000) may have been identical to those analyzed by King (1998) since King is included as an author but this is not explicitly stated. Guthery et al. (2000) did not differentiate habitat use by season and included data from both the summer breeding season and winter covey season. Additionally, they introduce a measure of cover that is directly related to the vulnerability to predators and evaluate this vulnerability at two levels: 1) the disc of vulnerability assesses the vulnerability to terrestrial predators at ground level, and 2) the cone of vulnerability assesses the vulnerability to aerial predators. The method and rationale for calculating these metrics can be found in Kopp et al. (1998). To relate to the work by King (1998), the disc of vulnerability can be compared to the mean vegetation structure at 15cm and 50cm whereas the cone of vulnerability can be compared to the mean vegetation structure at 1m and 2m. Despite these differences in sampling methodology, they found similar trends among used versus random sites to those of King (1998). In general, masked bobwhites selected areas with greater amounts of tall vegetation, woody vegetation, and lower temperatures at ground level than were randomly available. Guthery et al. (2000) speculate that the selection of tall vegetation and woody vegetation is a function of the high density of avian predators and the need for lower operative temperatures. They recommend increasing the amount of both woody and herbaceous cover (with a focus on herbaceous cover) to address both predation and thermal regulation. Guthery et al. (2001) also investigated habitat use under a multivariate perspective and found compensatory effects such that, under appropriate levels of all other cover variables, the optimal level of any one cover variable widened. For example, optimal levels of woody cover ranged from 15% to 40% unless other variables were in an acceptable range, in which case the optimal range expanded to between 0% and 45%.

2. Reproduction-

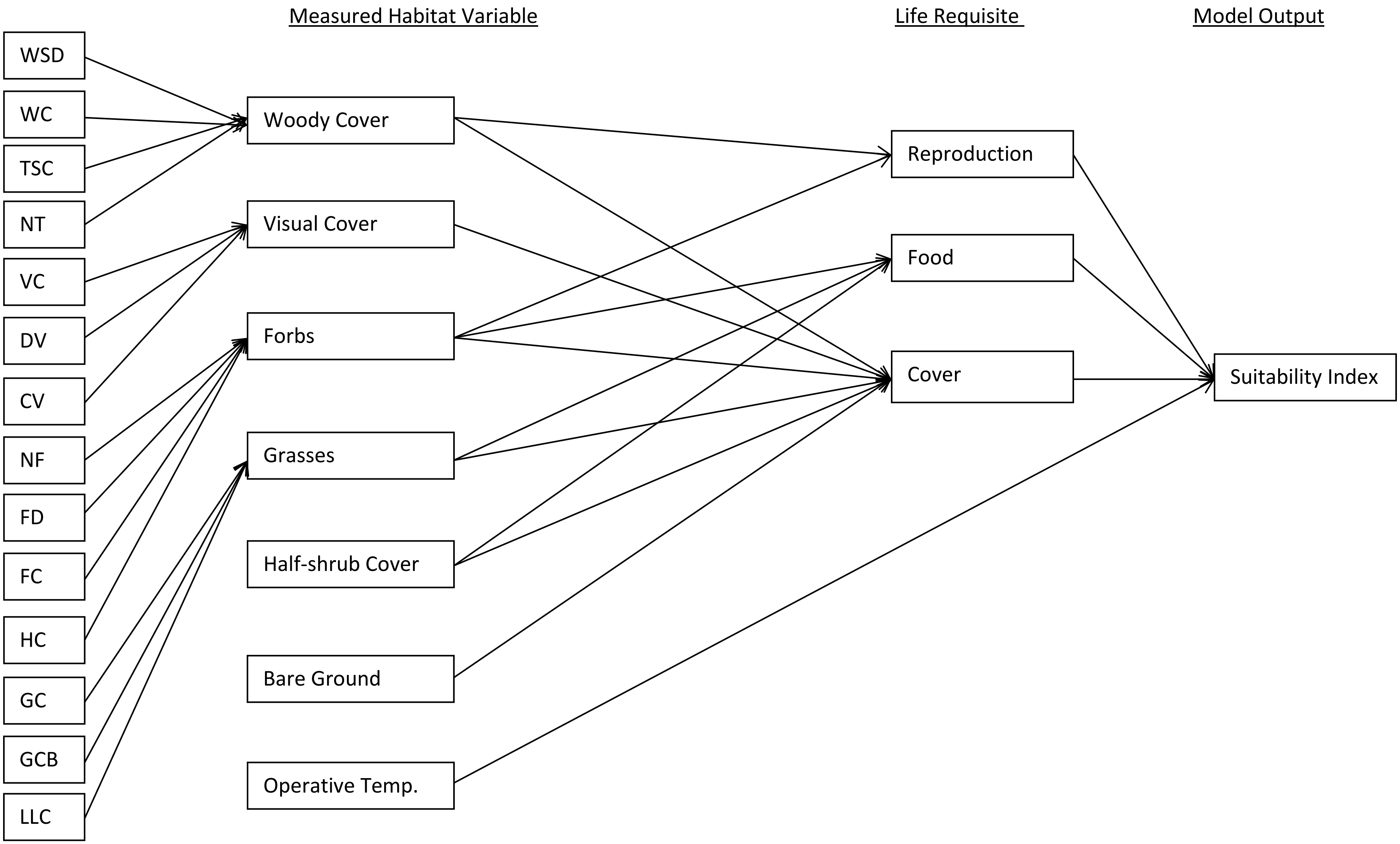
During the breeding season, King (1998) found that masked bobwhites preferred areas with a higher percentage of woody cover (18.17% vs 6.99%, *P*=.002) and trees (1 tree/ used point vs .99 tree/ random point, *P*=0.05). Similar to the non-breeding season, King also found that masked bobwhites preferred areas with taller vegetation, preferentially using areas with greater amounts of vegetation structure at 50cm, 1m, and 2m from the ground. King also found that breeding masked bobwhites preferred areas with a greater number of forbs (3.8/1,000 cm^2 vs 0.43/1,000 cm^2, *P*=.059) and half-shrub species (0.82/1,000 cm^2 vs. 0.66 /1,000 cm^2, *P*=0.040) than were randomly available on the landscape.

3. Food-

King (1998) found masked bobwhites preferred areas with greater numbers of native grasses than was randomly available. Greater numbers of grass species may provide higher food availability but no direct evidence supports this link aside from the early records of the diet of masked bobwhite described above (Table 1). Kuvleski et al. (2001) also speculated that native grasses and forbs may provide a better source of food for masked bobwhites than exotic grasses. Simms (1989) noted that although masked bobwhite utilized bufflegrass for cover, they were never far from native grasses and forbs and speculated that this was likely because native grasses and forbs were a necessary food source.

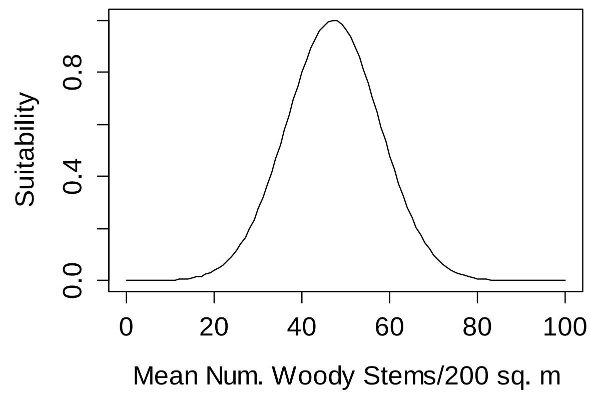
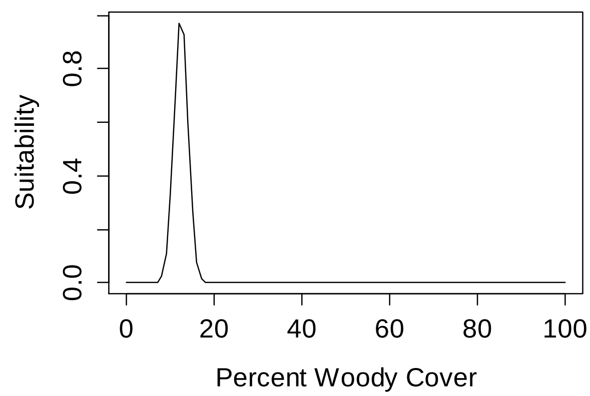
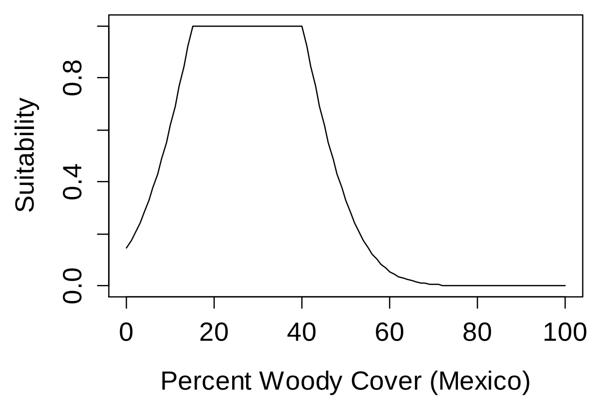
Section 3. Graphical Representation

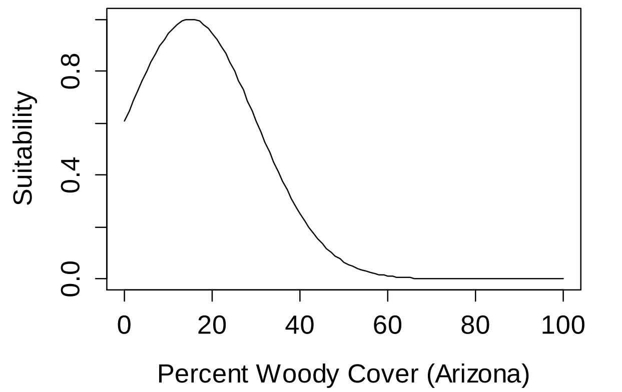
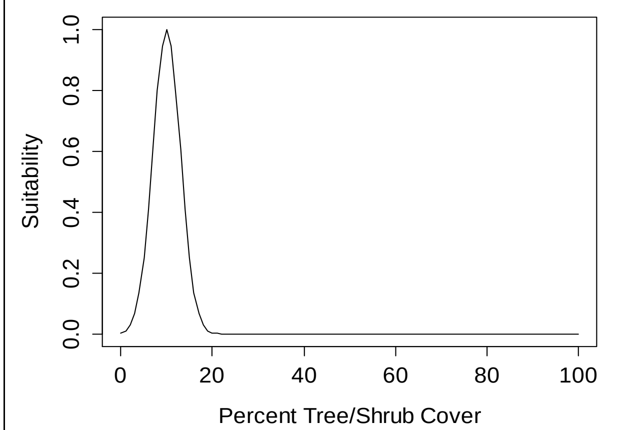
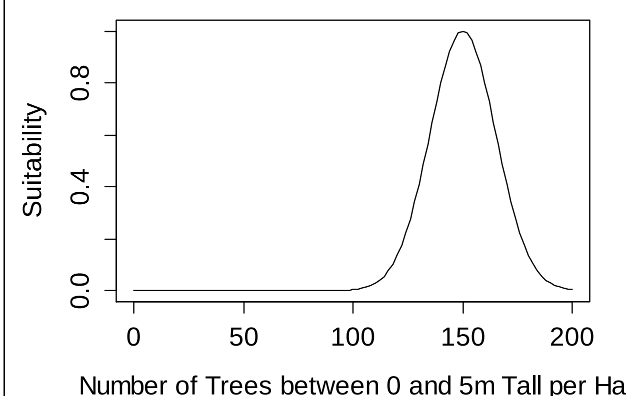
Figure 1. Relationship between measured habitat variables, critical life history requirements, and habitat suitability for masked bobwhites. Measured habitat variables listed below are described in section 4.

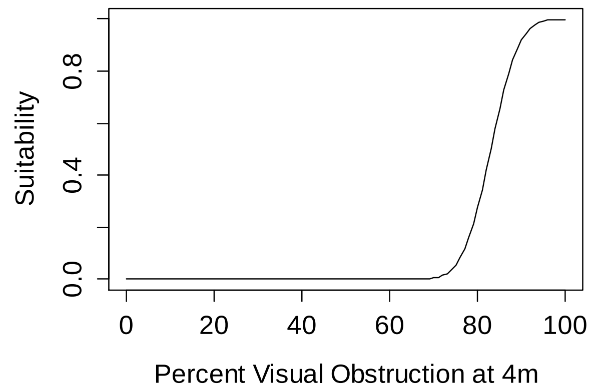
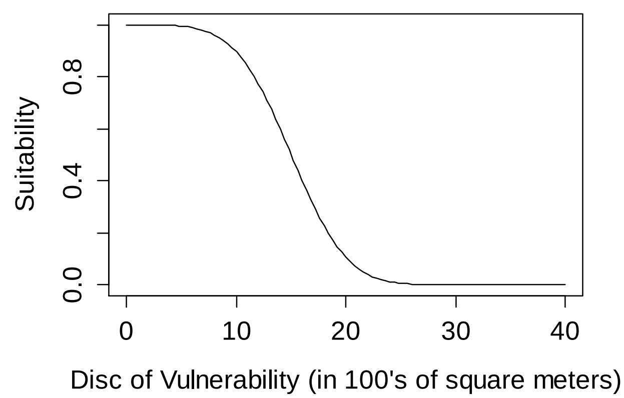
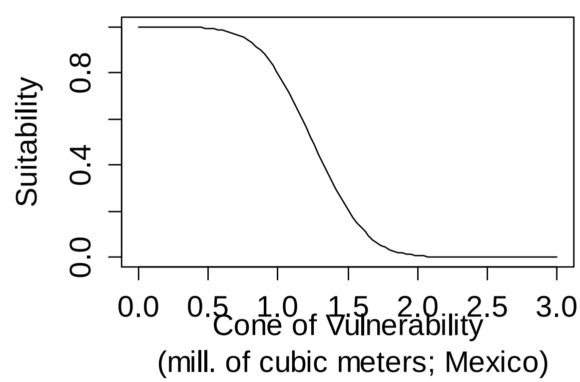


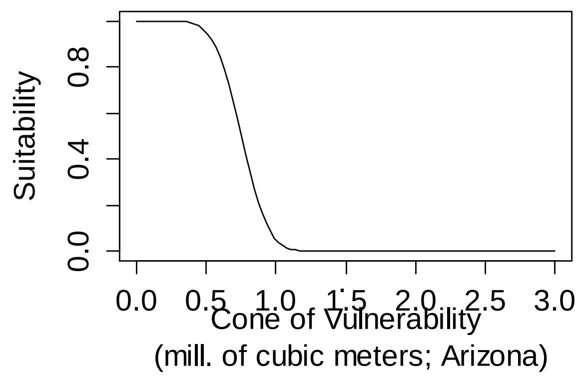
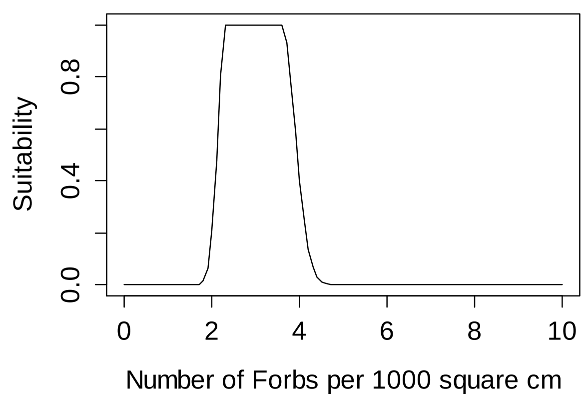
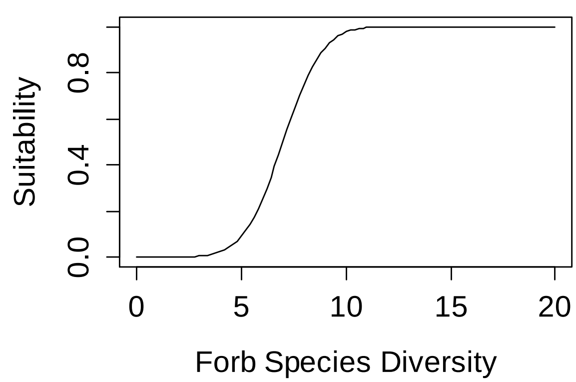
Section 4. Suitability Functions and Graphs

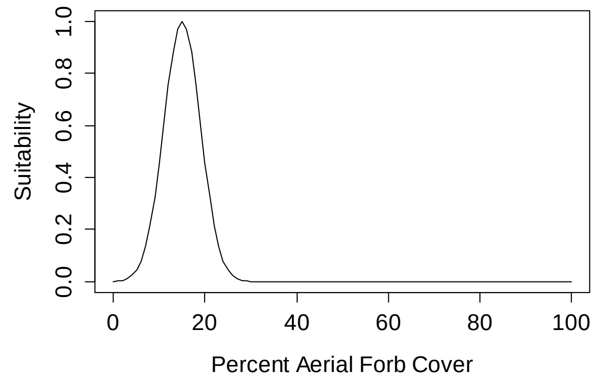
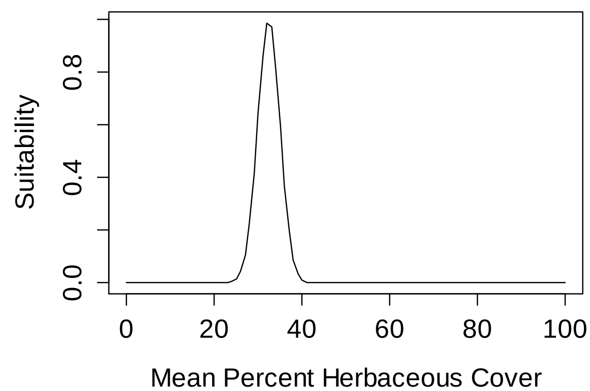
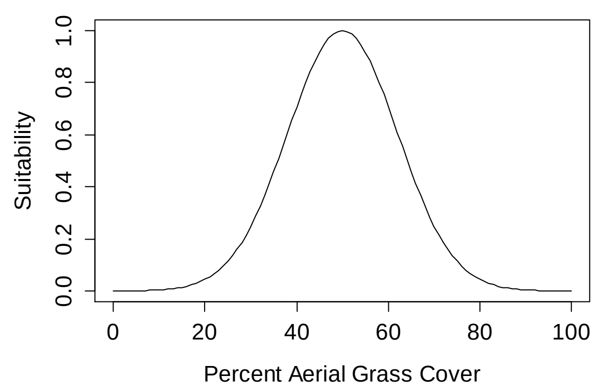
This section provides specific relationships between each habitat variable and suitability of the habitat for masked bobwhites while holding all other variables constant at their optimal levels. Several variables included here are redundant measures of the same habitat component but since the measures are functionally different they are still included.

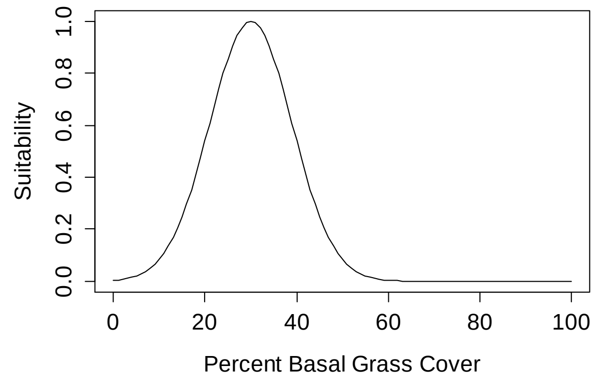
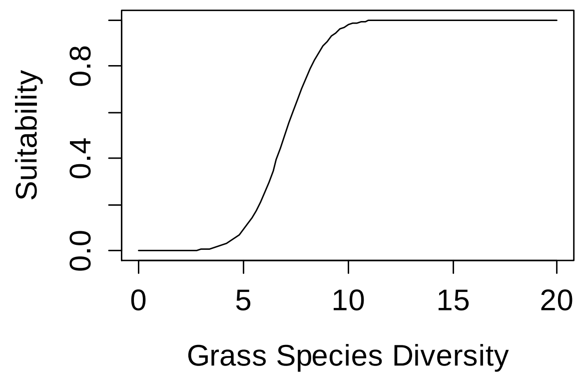
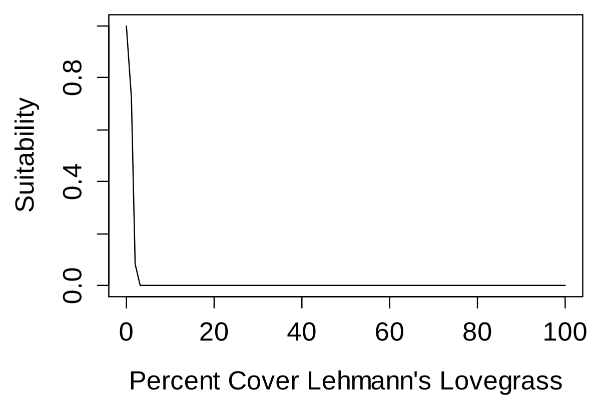
Variable	Description	Suitability Function	Suitability Graph
WSD	From King (1998): The mean number of woody stems >1m tall per 200 square meters.	$f(x) = \sqrt{2\pi 6654} exp\left\{\frac{1}{2}\left(\frac{x-47.1}{6654}\right)^2\right\}$*26.62039	
WC	From King (1998): Percent woody cover as measured in a line intercept method (Canfield 1941).	$f(x) = \sqrt{2\pi 2.56} exp\left\{\frac{1}{2}\left(\frac{x-12.38}{2.56}\right)^2\right\}$*4.010919	
WC	From Guthery et al. (2001): Percent woody cover in Sonora Mexico as measured in a line intercept method (Canfield 1941).	$f(x) = \begin{cases} \sqrt{2\pi 156} exp\left\{-\frac{1}{2}\left(\frac{x-27.5}{156}\right)^2\right\} * 51.66, \mathrm{x} < 15 \\ 1, \quad 15 < x < 40 \\ \sqrt{2\pi 156} exp\left\{-\frac{1}{2}\left(\frac{x-27.5}{156}\right)^2\right\} * 51.66, 40 < \mathrm{x} \end{cases}$	

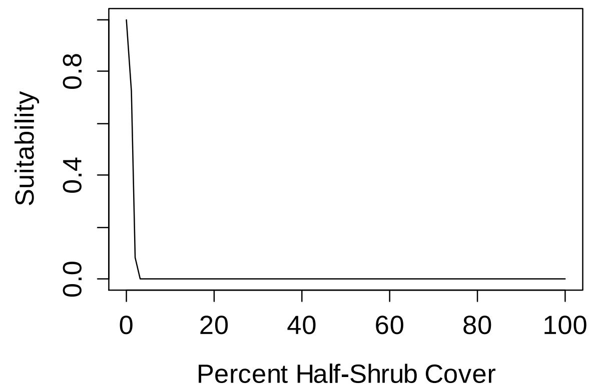
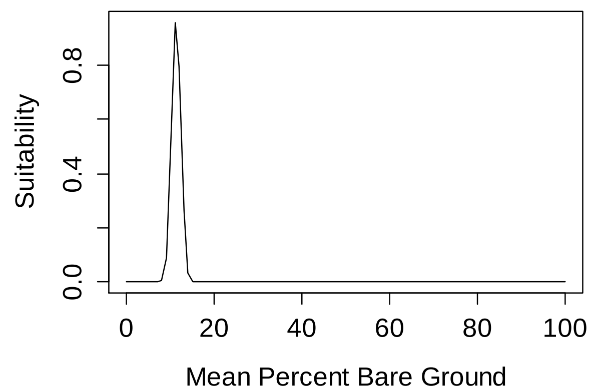
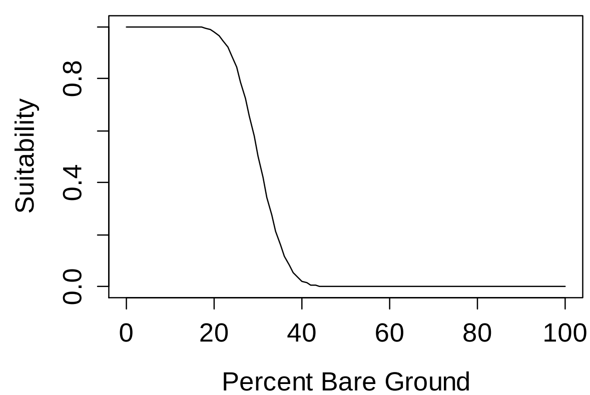
WC	From Guthery et al. (2001): Percent woody cover in Arizona as measured by a line intercept method (Canfield 1941).	$f(x) = \sqrt{2\pi 225} exp\left\{\frac{1}{2}\left(\frac{x-15}{225}\right)^2\right\}$*37.59943	
TSC	From Simms (1989): Percent tree and shrub cover as measured by a line intercept method (Canfield 1941).	$f(x) = \sqrt{2\pi 9} exp\left\{\frac{1}{2}\left(\frac{x-10}{9}\right)^2\right\}$*7.519885	
NT	From Simms (1989): Number of trees with a height between 0 and 5 meters per hectare.	$f(x) = \sqrt{2\pi 225} exp\left\{\frac{1}{2}\left(\frac{x-50}{225}\right)^2\right\}$*37.5994	

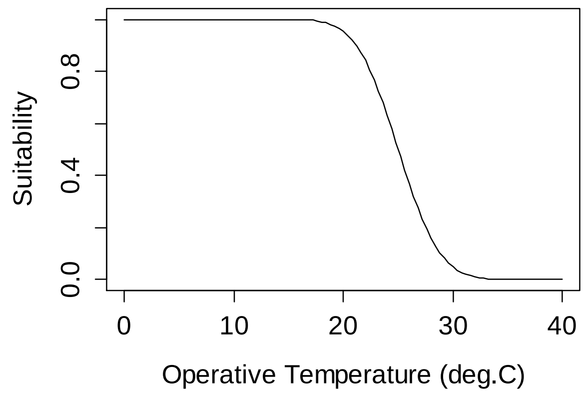
VC	From Simms (1989): Visual cover measured as percent visual obstruction of a vertical range pole (Robel et al. 1970) at a height of 1m and distance of 4m.	$f(x) = \frac{1}{2}\left[1 + erf\left(\frac{x-83}{\sqrt{2}(5)}\right)\right]$	
DV	From Guthery et al. (2000): Visual cover measured as a disc of vulnerability (as described in Kopp (1998)) around a random point.	$f(x) = 1 - \frac{1}{2}\left[1 + erf\left(\frac{x-15}{\sqrt{2}(4)}\right)\right]$	
CV	From Guthery et al. (2000): Visual cover measured as a cone of vulnerability (as described in Kopp (1998)) measured in millions of cubic meters around a random point.	<u>Mexico</u> $f(x) = 1 - \frac{1}{2}\left[1 + erf\left(\frac{x-1.25}{\sqrt{2}(.3)}\right)\right]$	

		<u>Arizona</u> $f(x) = 1 - \frac{1}{2}\left[1 + erf\left(\frac{x - 0.75}{\sqrt{2}(0.15)}\right)\right]$	
NF	From King (1998): The number of forbs counted per 1000 square centimeters (as in a Daubenmire frame (Daubenmire 1959)).	$f(x) = \begin{cases} \frac{\sqrt{2\pi.0324}exp\left\{\frac{1}{2}\left(\frac{x-2.32}{.0324}\right)^2\right\}}{2.202707}, x < 2.32 \\ 1, 2.32 < x < 3.58 \\ \frac{\sqrt{2\pi.0931}exp\left\{\frac{1}{2}\left(\frac{x-2.32}{.0931}\right)^2\right\}}{1.284235}, x > 3.58 \end{cases}$	
FD	From Simms (1989): Forb diversity as measured by the mean number of forb species as measured by the Daubenmire method (Daubenmire 1959).	$f(x) = \frac{1}{2}\left[1 + erf\left(\frac{x - 7}{\sqrt{2}(1.5)}\right)\right]$	

FC	From Simms (1989): Percent aerial forb cover measured as in a Daubenmire plot (Daubenmire 1959).	$f(x) = \sqrt{2\pi 16} exp\left\{\frac{1}{2}\left(\frac{x-15}{16}\right)^2\right\}$*10.02651	
HC	From King (1998): Percent aerial herbaceous cover measured as in a Daubenmire plot (Daubenmire 1959).	$f(x) = \sqrt{2\pi 6.5} exp\left\{\frac{1}{2}\left(\frac{x-32.39}{6.5025}\right)^2\right\}$*6.3919	
GC	From Simms (1989): Percent aerial grass cover measured as in a Daubenmire plot (Daubenmire 1959).	$f(x) = \sqrt{2\pi 144} exp\left\{\frac{1}{2}\left(\frac{x-50}{144}\right)^2\right\}$*30.07954	

GCB	From Simms (1989): Percent basal grass cover measured as in a Daubenmire plot (Daubenmire 1959).	$f(x) = \sqrt{2\pi 81} exp \left\{ \frac{1}{2} \left(\frac{x-30}{81} \right)^2 \right\}$*22.55965	
GD	From Simms (1989): Grass diversity as measured by the mean number of grass species as measured by the Daubenmire method (Daubenmire 1959).	$f(x) = \frac{1}{2}\left[1 + erf\left(\frac{x-7}{\sqrt{2}(1.5)}\right)\right]$	
LLC	From Simms (1989): Percent cover of Lehmann's lovegrass measured by the Daubenmire method (Daubenmire 1959).	$f(x) = 1 - \frac{1}{2}\left[1 + erf\left(\frac{x-1.3}{\sqrt{2}(0.5)}\right)\right]$	

HSC	From Simms (1989): Percent half-shrub cover measured by the Daubenmire method (Daubenmire 1959).	$f(x) = 1 - \frac{1}{2}\left[1 + erf\left(\frac{x - 1.3}{\sqrt{2}(0.5)}\right)\right]$	
BG	From King (1998): Percent bare ground as a cover percentage measured by the Daubenmire method (Daubenmire 1959).	$f(x) = \sqrt{2\pi 1.16} exp\left\{\frac{1}{2}\left(\frac{x-11.3}{1.16}\right)^2\right\}$*2.6069	
BG	From Guthery et al. (2001): Percent bare ground as a cover percentage measured by the Daubenmire method (Daubenmire 1959).	$f(x) = 1 - \frac{1}{2}\left[1 + erf\left(\frac{x - 30}{\sqrt{2}(5)}\right)\right]$	

OT	From Guthery et al. (2001): Operative temperature measured as described in Forrester et al. (1998).	$f(x) = 1 - \frac{1}{2}\left[1 + erf\left(\frac{x-25}{\sqrt{2}(3)}\right)\right]$	

Equations.

The final habitat suitability index score is a result of the combination of suitability scores from component variables. The equations which describe this combination are governed by the assumptions and relationships described in section 2.2. Additive equations imply each variable in the equation can compensate for other variables with low scores unless otherwise noted. Multiplication implies a score of zero for any variable results in a suitability score equal to zero (i.e., both variables must have non-zero scores for the area to be suitable).

$$Woody\ Cover = \frac{WSD + WC + TSC + NT}{4}$$

$$Visual\ Cover = \frac{VC + DV + CV}{3}$$

$$Forbs = \frac{NF + FD + FC + HC}{4}$$

$$Grasses = \frac{GC + GCB + LLC}{3}$$

$$Cover = \frac{Woody\ Cover + Visual\ Cover + Forbs + Grasses + HSC + BG}{6}$$

$$Food = \frac{Forbs + Grasses + HSC}{3}$$

$$Reproduction = \frac{Woody\ Cover + Forbs}{2}$$

$$Overall\ Habitat\ Suitability\ Index = \min(Reproduction, Food, Cover, Operative\ Temp.)$$

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