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QUANTIFYING SPECIES DISTRIBUTIONS FOR BIODIVERSITY ASSESSMENTS: SOME EXAMPLES APPLIED TO TREES, HERPETOFAUNA, AND BIRDS IN ONTARIO

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INTRODUCTION

Biodiversity conservation is a major operational challenge for resource managers and a major policy issue internationally (McKenney et al. 1994). One type of data required for quantitative analyses is accurate, scientifically based descriptions of species' potential and actual distributions. This is not a trivial exercise, as species are affected by numerous processes, including disturbance histories, climate, and nutrient regimes. Given the need for sound spatial descriptions, a major goal of the Bio-environmental Indices Project (BIP) has been the development of landscape-level descriptions of biodiversity (Mackey and McKenney 1994). This information is important for ecological restoration activities and reserve selection; it also creates a context for the controversies that exist over trade-offs between biodiversity conservation and wood production. Because the outputs are spatial data, results can be easily transferred and used by planners in geographic information systems (GIS).

The approach described here makes use of biological site data that are typically collected by field ecologists. Through various empirical methods, such data can be "spatially extended" across landscapes if spatial data on the drivers of ecological response are available (Nix 1986; Mackey 1993, 1994). This note describes a process that uses field observations to develop quantitative data on the distributions of species. Three examples are provided, using taxa that are of interest from a biodiversity conservation or wood production perspective in Ontario: jack pine (*Pinus banksiana* Lamb.), the five-lined skink (*Eumeces fasciatus*), Ontario's only lizard, and the American black duck (*Anas rubripes*), an important waterfowl species. The results are from various works in progress, and future papers by the authors will provide more detailed results and ecological interpretations of these analyses. The methods are being applied to a wide variety of Ontario's wildlife species and many commercial and noncommercial plant species.

It is worth noting a fundamental distinction between this landscape-level modeling and what often occurs in forest planning. Forest planning models (e.g., Ontario's new Strategic Forest Management Model; Davis 1995) typically aggregate Forest Resource Inventory (FRI) data that describe the major commercial tree species present and likely wood volumes in stands. These data are generated by mapping land units based on interpretation of aerial photographs, sometimes underpinned by field survey. Although a useful method of resource inventory, it provides no information about the causal processes—information that is essential for resource management. Also, links to other aspects of biodiversity are often made through expert opinions rather than through application of quantitative modeling and analysis. Examples include habitat suitability indices that relate forest type and stand age to a species' predicted preferred habitat. Habitat suitability indices are rarely spatially based and are projected based on assumed associations. The methods used here attempt to address more rigorously spatial variations that occur in forests and provide a more empirical basis to habitat suitability indices (e.g., Norton et al. 1992).

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MAJOR STEPS

This methodology aims to spatially extend biological site data by correlating the distribution of species with prevailing environmental conditions. These functions are then coupled to computer-based data, enabling those landscapes that are most suitable for the species to be identified. Three steps are required: 1) development of a spatial database of the independent variables that are correlated with the distribution of species; 2) compilation and analysis of data from a plot network of the target biological species; and 3) statistical analysis of the data from 1 and 2 so that spatial predictions of potential domains can be generated.

Spatial Database Development

The primary physical determinants of biological phenomena can be defined in terms of four environmental regimes: thermal, radiation, moisture, and nutrient regimes. Data on climate, terrain, and soil parent material are required to model these regimes across landscapes. Spatial models of climate and topography have been an important part of the BIP. "Climate surfaces" now exist that enable a large suite of climatic variables to be generated at any location in Ontario where latitude, longitude, and elevation are known. Mackey et al. (1996) describe the development of these climate surfaces and how they were used to produce a climatic classification of the province for comparison with Hills' site regions (a land classification system in use in Ontario; Hills 1960; Burger 1993). A major effort of the BIP has been the compilation of various biological surveys that are or can be georeferenced (i.e., assigned a longitude, latitude, and elevation). Thus, the suite of climatic variables can be appended to the survey data.

Digital elevation models (DEMs) are computer-based representations of topography in a regularly spaced grid of elevations. The grid is defined by gradients of longitude and latitude (or some other appropriate coordinate system). The climate surfaces can be coupled to the DEM using surface interrogation software, thereby generating gridded estimates. This enables the climate variables to be mapped in a GIS at a finer scale than previously possible.

A new DEM of Ontario has been created as part of the BIP (Mackey et al. 1994). Contour strings, stream lines, and point heights were taken from the Canadian National Topographic Series 1:250 000 digital data. These data were processed through the ANUDEM suite of software (Hutchinson 1989) to produce a DEM that supports a resolution of about ±5 m vertically and 100–150 m horizontally. DEMs have a wide range of uses in addition to mesoscale climate modeling (e.g., indices of slope, aspect, topographic wetness, catchment areas, flow paths; see Moore et al. 1991). A 1-km DEM was used in the spatial models presented here, as this is appropriate for regional analysis of mesoscale climate.

Compilation of Site Data

Ontario is rich with existing biological survey data sets. Examples include forest ecosystem and growth and yield plots (Sims and Uhlig 1992; Ontario Ministry of Natural Resources 1993; see also McKenney et al. 1995a); historical forest insect and disease surveys; various wildlife surveys, such as the aerial moose surveys, waterfowl surveys, and forest songbird surveys (Forest Bird Monitoring Program; Welsh 1995); and observations of reptiles and amphibians, as archived in the Ontario Herpetofaunal Summary database (Oldham and Weller 1992).

The Forest Ecosystem Classification (FEC) plot network is probably the most geographically extensive and intensively collected set of vegetation data available in Ontario. This was the source of data for the analysis of jack pine. Over 4100 plots now exist, primarily scattered throughout the middle third of the province. Although each region established its own protocols, the plots were, for the most part, relatively consistent in the attributes surveyed. Various characteristics were measured in a standard 10 x 10 m plot or quadrat, including presence and abundance of vascular plants (overstory and understory), soil properties, and diameter and age of dominant trees (see Sims and Uhlig 1992; McKenney et al. 1995a). Through a Collaborative Research Agreement with the Ontario Forest Research Institute of the Ontario Ministry of Natural Resources and the Canadian Forest Service, the FEC data have been compiled, location information has been checked, and estimates of various bioclimatic variables have been appended to the original data sets.

The Ontario Herpetofaunal Summary is a compilation of over 100 000 observations of the 58 species and subspecies of reptiles (30) and amphibians (28) that occur throughout Ontario. The summary is primarily a collection of amateur herpetologists' sightings since the mid-1980s. Location information such as a Universal Transverse Mercator (UTM) coordinate or latitude and longitude was recorded. Elevation data had to be appended to enable estimates of climate to be generated at the observation locations of the five-lined skink. This task was automated by linking the location information to the Ontario DEM.

The Canadian Wildlife Service (CWS) undertakes various bird surveys across Canada annually. Waterfowl surveys have been conducted in Ontario since the mid-1980s (Ross and Fillman 1990). In these surveys, helicopters are used to record the presence or absence of all waterfowl species in selected 2 x 2 km blocks during the breeding season in northern Ontario. Through a partnership with the CWS, a suite of bioclimatic variables has been appended to the historical northern Ontario waterfowl survey, which includes observations of the American black duck.

Spatial Predictions

Two approaches to making a spatial prediction of species' distributions are presented here. The first makes use of the BIOCLIM/BIOMAP suite of computer software developed by Nix (1986) and colleagues at the Australian National University. The second makes use of statistical models.

BIOCLIM makes use of the climate surfaces, DEM, and species' location information to produce bioclimatic profiles.

These profiles describe the climatic conditions sampled by the plot network (e.g., the range of mean annual temperatures, growing season length, annual precipitation). BIOMAP takes the BIOCLIM output and identifies (flags) grid cells that match the bioclimatic profile for the selected climatic variables. The resultant data can be input into a GIS and interpreted as a spatial prediction of the climatic domain of the species. In this way, landscapes that are climatically suitable for the species can be identified. Whether the species actually occurs there will depend on the influence of other environmental processes.

Figure 1 schematically represents the steps involved in the two approaches to making spatial predictions. Table 1 identifies the bioclimatic parameters that were used in the BIOMAP predictions presented here. BIOCLIM/BIOMAP is a repeatable and useful method for analyzing these types of survey data and can be easily updated with new observations.

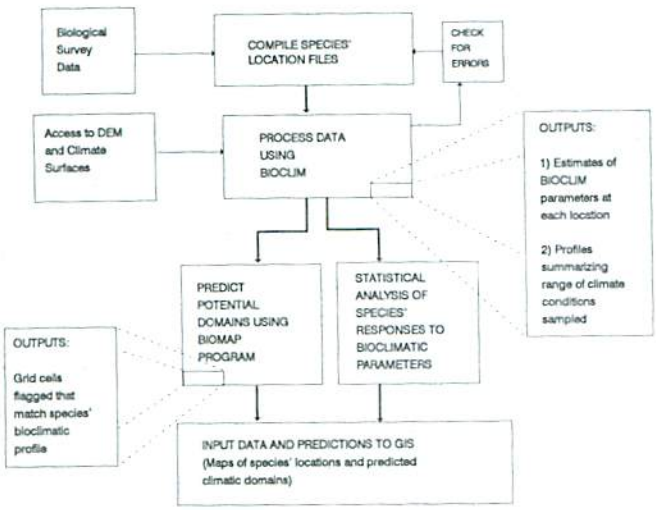


Figure 1. Steps involved in using BIOCLIM and making spatial predictions.

Source: Adapted from Lindenmayer, D.B.; Mackey, B.G.; Nix, H.A. The potential bioclimatic domains for four species of commercially important eucalypt tree species from south-eastern Australia (in review).

Table 1. Climate variables used in the BIOMAP procedure.

Thermal regime (°C)
Annual mean temperature
Annual mean maximum temperature
Annual mean minimum temperature
Maximum diurnal range
Mean temperature of the warmest month
Mean temperature of the coldest month
Seasonal range
Maximum temperature of the warmest month
Minimum temperature of the coldest month
Annual temperature range
Mean temperature of the warmest quarter
Mean temperature of the coldest quarter
Moisture regime (mm)
Annual precipitation
Precipitation seasonality
Precipitation of the warmest quarter
Precipitation of the coldest quarter

This approach to predicting the potential domain of species is transparent to interpretation. However, one limitation is that the selected climatic variables used in the BIOMAP predictions are all assumed to have an equal impact on the species' distribution. Note that statistical options are limited when the available data indicate only where a species is present—i.e., there are no observations of where it is absent. This was the case with the Ontario Herpetofaunal Summary.

In some cases (e.g., the waterfowl survey), both presence and absence information—i.e., known locations where the species did not occur as well as where it did occur—can be gleaned from the biological surveys. So-called inferential statistical models can then be undertaken, relating specific bioclimatic variables to the likely range or productivity of a species. The statistical model can then be linked to gridded estimates of the independent variables. For example, minimum temperature of the coldest month is often believed to be a key constraining variable limiting plant distributions. With presence/absence data, a logistic regression analysis can be used to quantify the probability of occurrence in relation to particular variables.

As an example, this method was applied to the waterfowl data, in particular to derive a probability of occurrence for American black duck. Through a stepwise regression procedure, six explanatory variables were chosen (these variables do not necessarily coincide with the variables listed in Table 1). The model had the following form:

$$\ln\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6$$

where p is the probability of not occurring (i.e., seeing no duck), the independent variables are:

- x_1, annual mean minimum temperature
- x_2, maximum diurnal range
- x_3, mean temperature of the coldest quarter
- x_4, annual mean radiation
- x_5, lowest monthly radiation
- x_6, growing degree days during the growing season

and βs are parameters generated by the statistical analysis. After the β parameters were estimated from the sample data, the following equation was used to estimate probability of occurrence (i.e., seeing at least one duck):

$$q = 1 - \frac{\exp(b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_5 x_5 + b_6 x_6)}{1 + \exp(b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_5 x_5 + b_6 x_6)}$$

where q is the probability of occurrence and b's are estimated parameters of β's. This statistical function was then coupled to gridded estimates of the six independent variables to generate a probability of occurrence at each grid cell.

RESULTS

Figure 2 presents an example of bioclimatic profiles for the three species using the eight climate variables chosen by Mackey et al. (1996) in their climate classification of the province. For each location where the species occurred, these variables were estimated. When displayed in a cumulative frequency plot, the climatic envelope for each variable is easily visualized. For some variables, the species occur in very similar environments; for other variables, each species has a distinctive response. The five-lined skink, for example, occurs in much warmer and wetter conditions than the other species; relative to jack pine, American black duck occurs in a cooler thermal domain (i.e., lower maximum temperature of the warmest month, shorter growing season, fewer degree days during the growing season). In future work, these relations will be investigated more thoroughly from an ecological perspective. What energetics are involved? Which variables are important? Which species share similar potential climatic domains? Can ecological theory help to explain the patterns? How can topographic and substrate data be factored in to the predictions of species' potential environmental domains?

Figures 3, 4, and 5 are spatial predictions (on a 1-km grid) of the three species' potential climatic domains. In addition

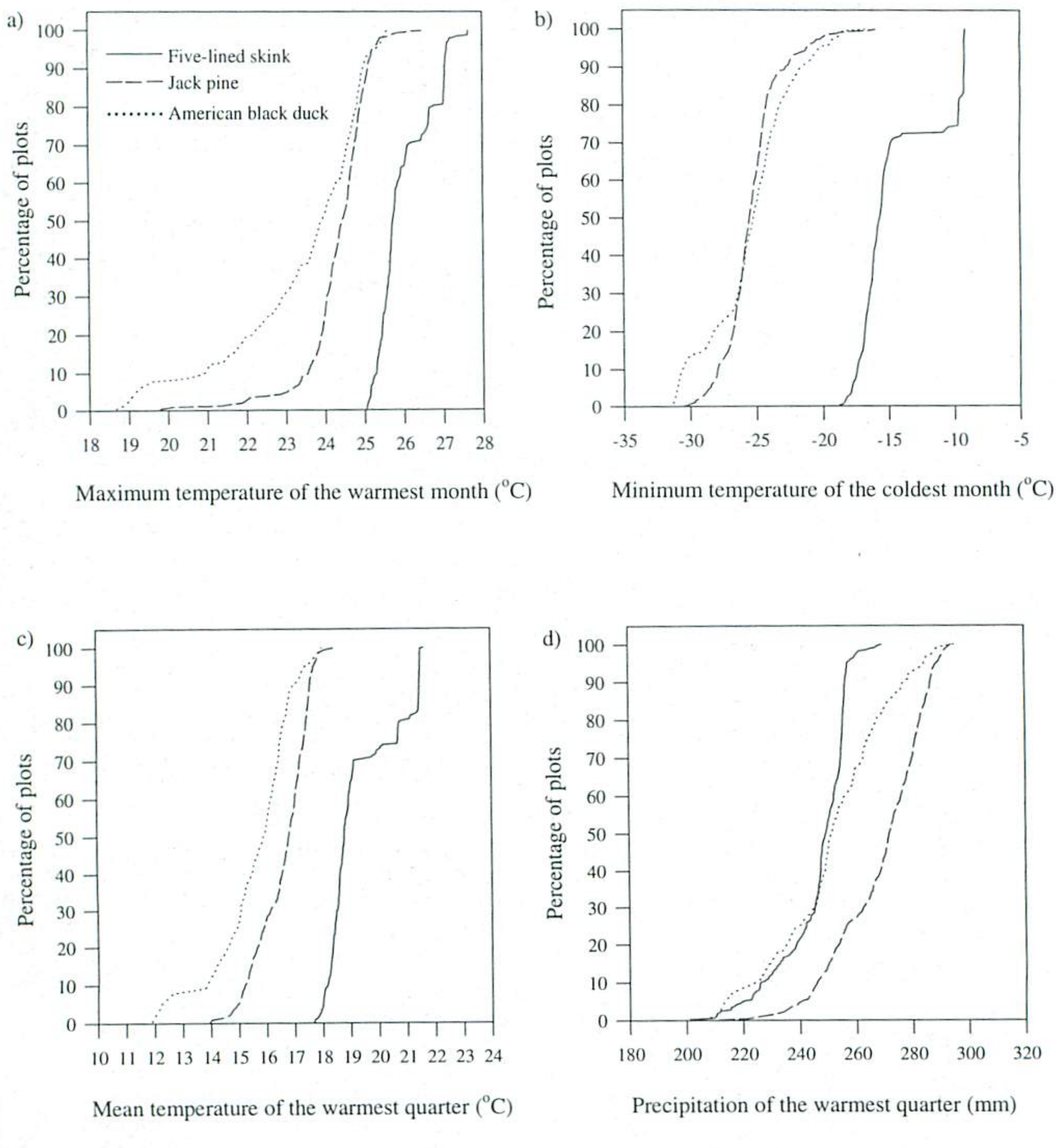
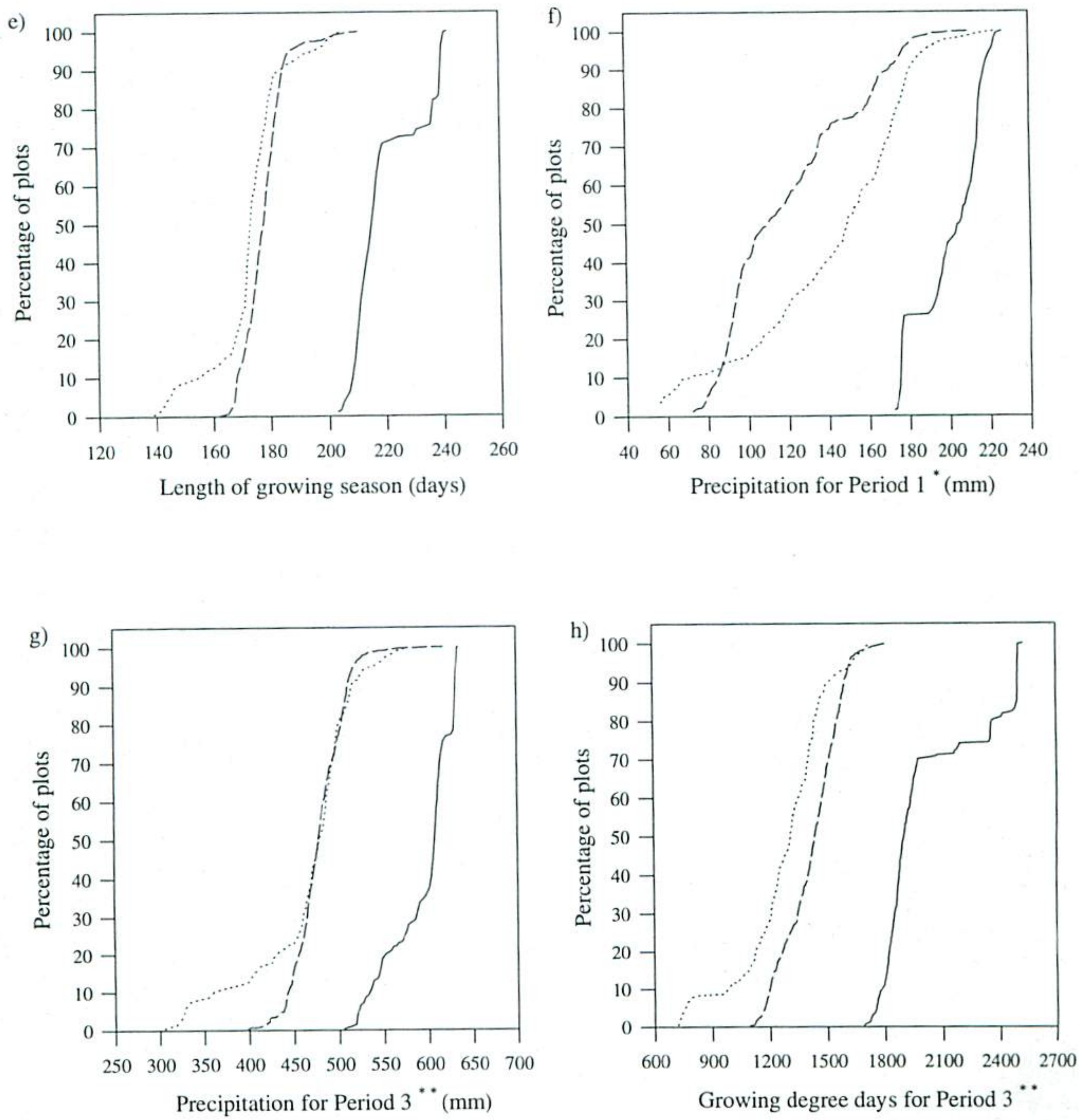


Figure 2. Bioclimatic profiles.

to the environmental variables noted above, remotely sensed data can be used to further refine these predictions by masking land cover types such as urban centers that are no longer appropriate habitat.

Figure 3 is a BIOMAP of jack pine based on the analysis of province-wide FEC data. Jack pine is a boreal species, whereas the five-lined skink (Fig. 4) occurs primarily in southern Ontario. The darkest areas represent the "core" (10–90 percentiles) climate domain for the species. The 10–90 percentiles are the climatic conditions where most of the site data occur according to the bioclimatic profiles. The lighter shade of gray indicates those grid cells that fall within the range (1–100 percentiles) of climatic values defined by the survey data, indicating more marginal conditions. The intermediate areas are defined by the 5–95 percentiles.

Figure 4 is a BIOMAP of the five-lined skink. The actual sightings for the skink are noted. This gives rise to several interesting observations. The first is that a large amount of the core area occurs in part of southern Ontario where no actual sitings have occurred. This simply indicates that the climate in these areas is most similar to the climate where the species has actually been observed. Skinks may not have been observed here because of sampling biases and/or lack of habitat. This information could therefore be useful for



* Period 1 is the three-month period occurring prior to the start of the growing season.
** Period 3 is the total growing season.

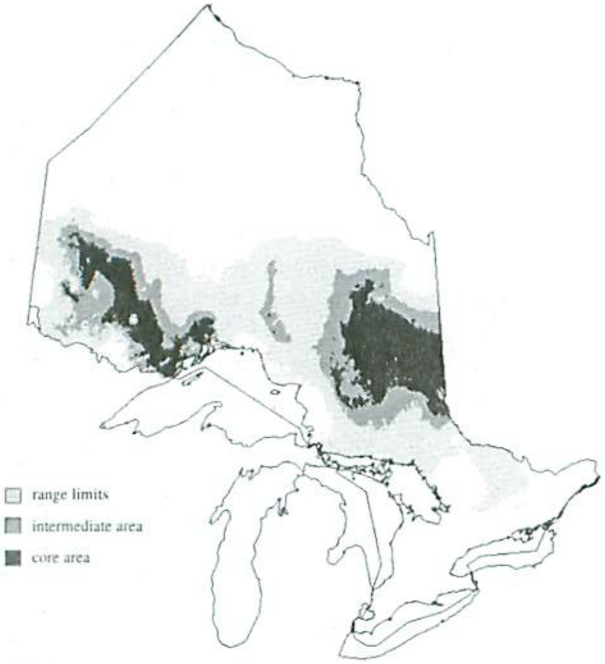


Figure 3. A climatic domain for jack pine in Ontario.

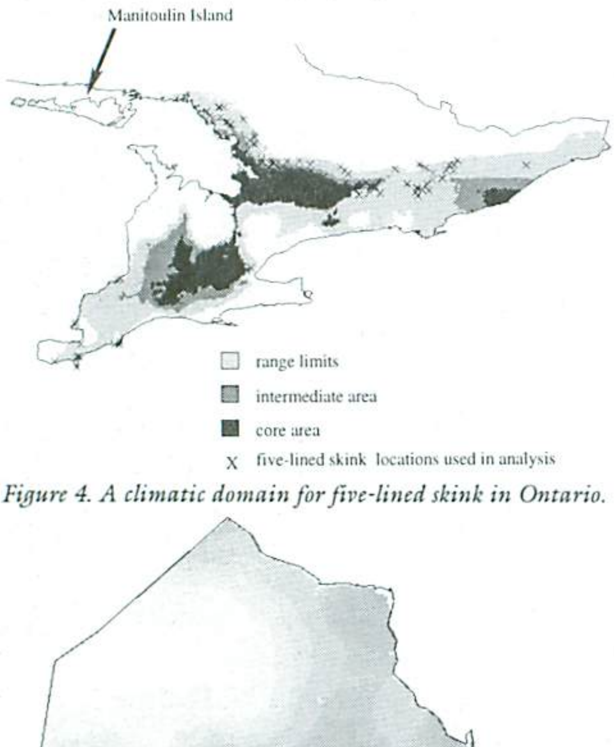


Figure 4. A climatic domain for five-lined skink in Ontario.

Figure 5. Probability of occurrence of American black duck in Ontario.

habitat restoration activities and future surveys. Several of the sitings occur in the range limits, and there may be some question as to why they are not identified as part of the core area. This reiterates that all of the BIOMAP climatic parameters must be within the 10–90 percentiles to flag a grid cell as a core area and also identifies some limitations of presence-only data. Another outcome is the prediction that the far western portion of Manitoulin Island is climatically suitable habitat for the skink.

Figure 5 is a prediction of the probability of occurrence of American black ducks across the entire province using presence/absence data. Low probabilities exist in the northwest and southwest. Higher probabilities occur in the northeast and north of Thunder Bay at the northwest corner of Lake Superior. The predicted distribution is very close to the observed abundance distribution patterns described by other integrative approaches. These predictions can be augmented in the future as other data, such as amount and type of water in the plot area and the ruggedness of the landscape, are incorporated into the analyses. These are variables that can, in principle, be generated through analysis of the Ontario DEM. In addition, there are plans to incorporate a coarse-scale surficial/bedrock geology nutrient classification of the province to help refine the predictions. Nevertheless, according to CWS experts, the current probability map is already a good geographic representation of American black duck habitat and corresponds well with what is known about its distribution.

CONCLUDING COMMENTS

The demand for clear evidence of sustainability in natural resource use and effective biodiversity conservation now requires managers to incorporate a broad range of information in land use planning. Although new information is certainly required, strong efforts must be made to use existing data effectively. The methods described here are a promising approach to adding value to existing biological surveys. In principle, they can be applied to any biological data to which latitude, longitude, and elevation can be appended. The result is new quantitative georeferenced data that can be integrated with other knowledge and information about species' habitat requirements.

In the future, it is hoped that these methods will be applied to most of Ontario's plant and animal species and that the resultant data and predictions will be available for land use planning and further research. For example, BIOMAPs or other types of spatial predictions could be used as a basis for stratifying the province for biodiversity monitoring or establishing new research plots (e.g., McKenney et al. 1995b). The task is not as daunting as may first seem, given the availability of survey data and the computer-based technology described above. These georeferenced data can also be significantly enhanced by incorporating other types of spatial data, such as vegetation cover (e.g., Landsat imagery) or forest type (e.g., FRI) data. Much finer-scaled information could result. This will be one thrust of future collaborations by the authors.

Significant research remains to be undertaken to determine the optimal analytical strategy for different survey data types. In addition, a challenge remains in developing ecological interpretations and making use of the data for policy development. In the latter case, such data could be used as baseline information for indicators of sustainable development—e.g., in assessing the adequacy with which parks and reserves capture samples of Ontario's biological heritage. Given declining research dollars, it is imperative that research agencies work in partnership to maximize the value of existing data sets for taxpayers.

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