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TOWARDS ENVIRONMENTAL STRATIFICATIONS FOR OPTIMIZING FOREST PLOT LOCATIONS

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INTRODUCTION

An important problem in field surveys and ecological monitoring is where to locate plots and determine how many plots there should be. When the aim of a survey is to examine the extent to which variance in biological data is correlated with environmental gradients, the survey design must ensure that 1) plots are located so as to yield a representative sample of the range in hypothesized causal environmental conditions, and 2) sufficient replicates of the environmental conditions are sampled for statistical testing purposes. These objectives are not easily achieved and, consequently, field survey design often has a highly subjective basis. To provide an objective basis for the efficient design of environmental surveys, accurate information is required about the spatial distribution of the key biophysical variables of interest.

The objective of this note is to introduce two concepts relevant to stratifying the environment for locating potential plots. The first concept arises out of the integration and analysis of site data in relation to spatial databases. Faster computers, spatial data, and Geographic Information Systems (GIS) make this type of analysis more feasible than was previously possible. The second concept simply makes further use of available spatial databases. These spatial databases quantify processes that drive biological response. For example, in theory these processes help explain the distribution and productivity of jack pine (*Pinus banksiana* Lamb.), black spruce (*Picea mariana* [Mill.] B.S.P.), or the boreal chickadee (*Parus hudsonicus* Forster). By interrogating these spatial databases it is possible to more rigorously identify potential new plots. For example, a field program could be designed using a climate classification of the province as a stratification. Plot locations could be referenced by these data. Other spatial data, such as satellite images of vegetation cover or forest resource inventories and road networks, are also available in some parts of the province. Use of this data can help the stratification process.

To illustrate the advantages of employing spatial databases in survey design, three existing survey systems for monitoring insect, disease, and forest health monitoring sites in Ontario were used. The Canadian Forest Service is involved in a number of annual and periodic surveys to assess pest impacts and forest health. These surveys directly support forest management decisions. In some intensive studies, field plots are virtually unreplicated; at the other extreme are forest health monitoring systems that involve the placement of numerous plots across the entire province. The current analysis was done in the context of Ontario's climate and follows from the assessments of representativeness on forest ecosystem and growth and yield data as reported by McKenney et al. (1995). Climate has a pervasive influence on the distribution and abundance of organisms and is therefore a relevant characteristic under which to organize regional ecological surveys. It is likely that a better understanding of disease/climate or insect/climate relations will result in the establishment of spatially explicit hazard zones and ratings.

SITE DATA

Four forest survey data sets were used to explore the concepts and approach. As long as locations can be reasonably georeferenced (i.e., location in terms of latitude, longitude,

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and elevation), the methods described here can be applied to any previously collected biological survey. Thus, the first step was to append latitude, longitude, and elevation to those data sets described below.

Scleroderris

Extensive surveys for scleroderris canker caused by the fungus *Gremmeniella abietina* (Lagerb.) Morelet have been undertaken in Ontario since 1966 (Sippell et al. 1966). After discovery of the more damaging European race of the disease in Canada in 1978, more formal surveys were undertaken. Presently, each Forest Insect and Disease Survey (FIDS) Unit field technician working in the area from Lake Nipissing south to 44° N latitude is required to survey for the disease in existing red pine (*Pinus resinosa* Ait.) plantations. Each technician surveys a minimum of 20 sites and records the presence or absence of the disease. Disease incidence on infected sites is also determined. Between 1963 and 1994, 272 locations were identified as being infected with scleroderris. Two races of the disease currently exist in Ontario; the North American strain, which primarily infects jack pine and red pine and the European strain, which primarily infects red pine. The North American race occurs across the range of pines in the province, but the European race exists only between 46°–44° N latitude. Climate probably prevents occurrence of the disease below this latitude (Hopkin and McKenney 1995).

Acid Rain National Early Warning System (ARNEWS)

The ARNEWS plot network was established in 1985 as part of a national network to assess the impact of pollutants on tree species in Canada, and to monitor any changes that might occur in forested regions by recording pest and abiotic damage. The system monitors all major tree species, soils and foliage chemistry, ground cover, and mensurational data (D'Eon et al. 1994). The ARNEWS consists of 38 plot locations in Ontario and 151 nationally.

Jack Pine Budworm

As part of normal spray operations, more than 1 000 point samples of jack pine budworm (*Choristoneura pinus* Free.) populations were taken in northern Ontario between 1984 and 1987. All points were within areas identified by aerial reconnaissance as having endured at least 1 year of defoliation (Meating et al. 1995).

Forest Ecosystem Classification Plot Data

Ontario's Forest Ecosystem Classification (FEC) systems are based on one-time measurements of a network of mature, natural forest stands over 50 years of age. To date, over 4 100 such plots have been established. Numerous soil, vegetation, and forestry attributes are measured within 10-m x 10-m plots. Because the plots are generally well distributed geographically across the province, this survey data is suitable for defining the potential ranges of some tree species (Sims and Uhlig 1992, McKenney et al. 1995).

METHODS AND RESULTS

Towards an Environmental Stratification

The first step involved in developing an environmental stratification is to define the spatial limits of the problem of interest. Three techniques were utilized for this type of assessment. One technique involved comparing the distribution of existing survey plots against selected pairs of climatic gradients (Two-dimensional Climate Domain). The second involved a Bioclimatic Analysis of the potential geographic distribution of red pine and scleroderris. The last approach entailed overlaying the locations of existing (or potential) survey plots onto derived climatic classifications of the province (Environmental Domain Interrogation). These methods provided different perspectives on the extent to which the survey plots collectively sampled climatic gradients in Ontario.

Two-dimensional Climate Domain Analysis: A Provincial Look

The Ontario climate model described by Mackey et al.[1] permits the estimation of long-term mean monthly climatic parameters (e.g., mean annual temperature) for any location in the province for which the latitude, longitude, and elevation are known. Table 1 lists a number of long-term climatic variables that can now be generated at the point of survey. Errors associated with climate estimates are approximately ± 0.5°C for temperature variables and 8% for precipitation. By coupling these surfaces to a new digital elevation model (DEM) for Ontario (Mackey et al. 1994), estimates of a suite of climatic parameters were generated for each point on a regular grid with a resolution of approximately 1 km. Two pieces of software perform this task — BIOCLIM (Nix 1986) and ONTCLIM, developed by J.P. McMahon and reported in Mackey et al.[2] For this exercise, data from north of 52° N latitude were excluded so that only the forest zone of commercial interest in Ontario was analyzed (*see* Figure 1). This subset of the full 1-km grid for Ontario generated 500 461 grid points. The Ontario climate model was also used to estimate the various climatic parameters at each of the plot locations.

From the suite of possible combinations, the two-dimensional climate analysis was illustrated using the maximum temperature of the hottest month and the minimum temperature of the coldest month. These variables were selected because they illustrate the range of temperature experienced in the province.

In Figure 2 the gray (■) background represents the climatic domain occupied by Ontario's productive forests, as defined by the gridded estimates of climate with respect to

[1] Mackey, B.G.; McKenney, D.W.; Yin-Qian, Y.; McMahon, J.P.; Hutchinson M.F. Site regions revisited: A climate analysis of Hills' site regions for the province of Ontario using a parametric method. Canadian Journal of Forest Research. (In press.)
[2] Ibid.

Table 1. Climate variables generated for each forest survey plot.

Thermal

Annual mean temperature
Annual mean maximum temperature
Annual mean minimum temperature
Annual diurnal range
Mean temperature of the hottest month
Mean temperature of the coldest month
Mean seasonal range
Maximum temperature of the hottest month
Minimum temperature of the coldest month
Annual temperature range
Mean temperature of the wettest quarter
Mean temperature of the driest quarter
Mean temperature of the hottest quarter
Mean temperature of the coldest quarter
Julian day of the start of the growing season
Julian day of the end of the growing season
Growing season duration
Growing degree-days for Period 3
Growing degree-days for Period 4
Mean temperature for Period 3
Temperature range for Period 3

Moisture

Annual precipitation
Precipitation of the wettest month
Precipitation of the driest month
Precipitation range
Precipitation of the wettest quarter
Precipitation of the driest quarter
Precipitation of the hottest quarter
Precipitation of the coldest quarter
Precipitation for Period 1
Precipitation for Period 2
Precipitation for Period 3
Precipitation for Period 4

Radiation

Annual mean radiation
Highest monthly radiation
Lowest monthly radiation
Radiation range
Radiation of the wettest quarter
Radiation of the driest quarter

Definitions:

1. Annual diurnal range — the difference between the annual mean maximum temperature and the annual mean minimum temperature.
2. The growing season start — the Julian day number of the last day of 5 consecutive days when the mean daily temperature is above 5°C.
3. The growing season end — the Julian day number of the first day from August 1 with a minimum temperature less than -2°C.
4. Growing season duration — the difference between the growing season end and the growing season start.
5. Period 1 — 3 months prior to the growing season.
6. Period 2 — 6 weeks from the start of the growing season.
7. Period 3 — the total growing season.
8. Period 4 — the difference between Period 3 and Period 2.
9. Precipitation range — the difference between precipitation of the wettest month and precipitation of the driest month.
10. Radiation range — the difference between the highest monthly radiation and the lowest monthly radiation.

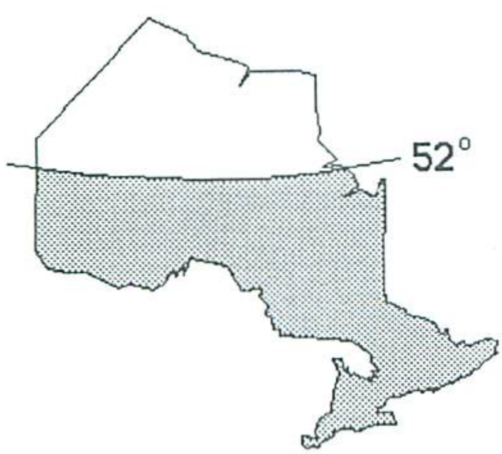

Figure 1. Ontario south of 52° N latitude, as used in the climate domain analysis.

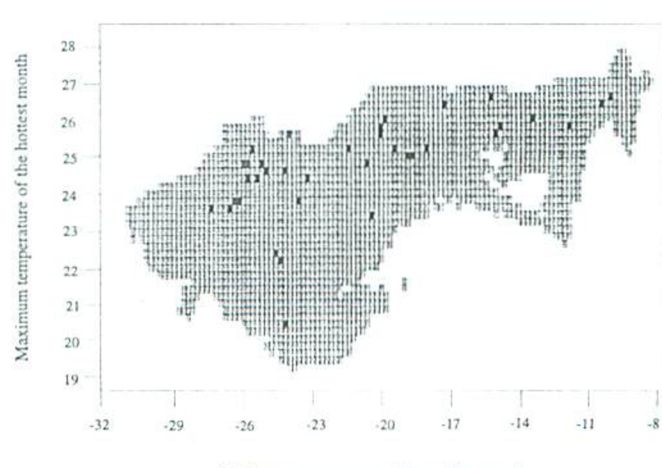

Figure 2. Climatic distribution of ARNEWS plots.

the pair of variables on the axes. Overlaid are the climate estimates for the same pair of variables at each ARNEWS plot. These are depicted by the black squares (■). The ARNEWS plots seem to be broadly distributed across this two-variable climate regime, although there appear to be relatively few plots in areas bounded by -20°C to -30°C minimum temperature of the coldest month and 19°C to 23°C maximum temperature of the hottest month. This result follows from the way in which ARNEWS plots were generated. Each district in the province had a fixed number of plots to establish. Thus, the plots are generally evenly distributed across the province and over climate regimes.

Two-dimensional Climate Domain Analysis: A Species/Host Look

The second approach focused on species/host/climate relations. This is illustrated by using the jack pine budworm and FEC plot data sets. The concept is the same as previously described except that the climatic range of the host tree was used (as defined by the FEC data system), not the gridded climate estimates for all of Ontario south of 52° N latitude. Overlaid on the climatic range for jack pine was the climatic range for jack pine budworm, based on the budworm field observations described above. The same two variables were selected for this analysis.

The jack pine budworm data set appeared "clumped" in a warmer climate regime than did jack pine itself (*see* Figure 3). Most of the budworm plot locations experienced a maximum temperature of the warmest month greater than 24°C and a minimum temperature of the coldest month ranging

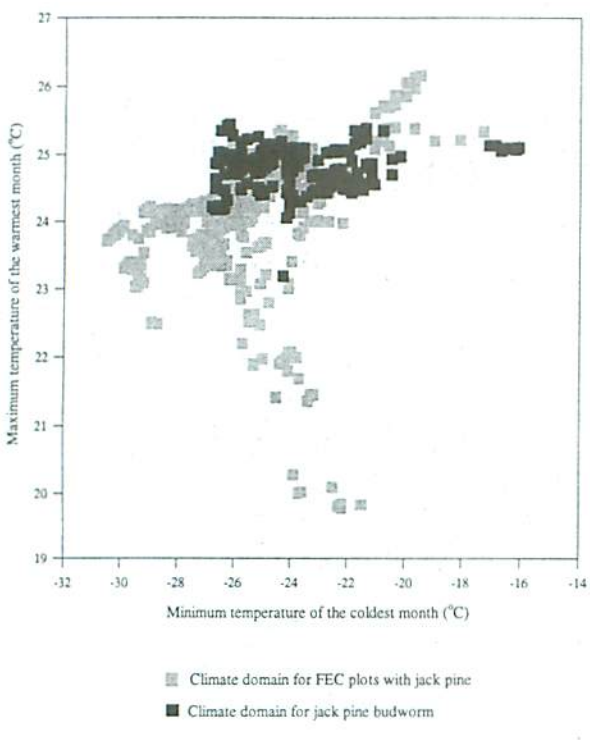

Figure 3. Jack pine budworm/jack pine climate domain analysis.

between -27°C and -16°C. Once again, the distribution of plots can be explained by the objectives of the survey. In this case, only budworm outbreaks were surveyed. Interestingly, outbreaks (and thus surveys) appear to be restricted to a particular climatic range. This analysis lead to new hypotheses concerning outbreaks. Specifically:

1) Insect outbreaks only occur in these particular climatic envelopes (this will be statistically evaluated in future work).

2) The dynamics of the insect are such that it is expanding to other areas, but has not reached these yet (again, an empirical question).

A Bioclimatic Analysis of Red Pine and Scleroderris

This section describes preliminary results that will be more fully reported in the future.[3] Bioclimatic profiles for both red pine (using the FEC data) and scleroderris were generated using the BIOCLIM program (Nix 1986). This bioclimatic profile was generated for 16 climatic variables. An example of one variable (mean annual temperature) is shown in Figure 4. At each location where red pine occurs

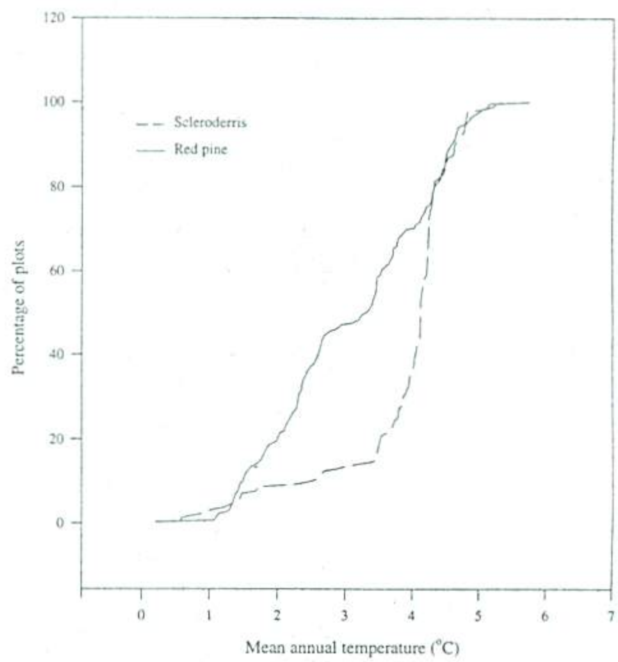

Figure 4. Cummulative frequency plot of mean annual temperature for red pine and scleroderris.

in the FEC data set, mean annual temperature was estimated. The same process was followed for the scleroderris data. The cumulative frequency plots for red pine and scleroderris suggest that each species occurs in different climatic envelopes; 10–90% of the scleroderris plots fall between ~2.5–4.7°C whereas 5–95% of the red pine plots fall between ~1.5–4.7°C. To make provincewide predictions regarding the potential distribution of red pine and scleroderris, the climatic profile was matched with estimates of all 16 climatic values on a 1-km grid basis. If all climate values were within the specified range that grid point was

[3] Mackey, B.G.; McKenney, D.W.; Grott, U.; Sims, R.A. A bioclimatic analysis of trees and selected understorey plants in Ontario. (In prep.)

flagged. The result was a data file containing coordinates of each grid cell where the climate matched, and which could then be used in a GIS for display and further analysis (e.g., stratifications).

Figures 5 and 6 show the potential climatic domains for red pine and scleroderris using the grid-matching methods described above. The dark area identifies the grid points whose climatic parameters lie within the upper and lower limits of the species profiles (i.e., the climatic range). The lighter shades identify the regions where the climate matches within the 5–95 and 10–90 percentiles, respectively. The red pine predictions were based on the FEC data, which samples its natural distribution. Overlaid on this image are the plot locations where scleroderris canker has been observed in red pine plantations. An interesting outcome of this exercise was the observation that a large portion of the scleroderris plots found on red pine fall outside of the predicted climatic domain of naturally occurring red pine. This raises some questions about where red pine plantations are being established in Ontario, and the seed sources for those plantations. Plants are generally considered to be genetically adapted to the climate of their origin. It may be the case that red pine plantations are being established outside of the climatic domain for naturally occurring red pine, or that scleroderris is associated with plantation silviculture. This could have implications for growth and yield. Figure 6 displays the potential distribution of scleroderris across Ontario. Gridded data such as these could be used to help stratify future plot locations and to examine the important implication of planting red pine outside of its apparent "natural" range. Clearly this is an area that requires further research.

Environmental Domain Interrogation System

The Environmental Domain Interrogation System (EDIS) is a decision support tool being developed as part of the Bio-environmental Indices Project (BIP) (Mackey and McKenney 1994). EDIS can be used to evaluate the representativeness of plot locations by calculating the extent to which plots or a network of polygons (e.g., parks) sample an environmental classification. Plot or polygon positions are overlaid onto a previously developed grid, which represents an environmental gradient of interest. Hills' site regions is an example of an environmental classification (Hills 1959). The number of plots that occur in each class is summed, or if polygons are used, the relative area of each class captured by the polygon is calculated. EDIS was used to assess the representativeness of the three health and insect forest plots in terms of a new climate classification of Ontario (Mackey et al.[4], McKenney et al. 1995).

Development of Climate Classifications Used in EDIS Analysis

New climatic classifications for Ontario were generated using the computer based classification method developed by Mackey et al. (1988). These classifications are discussed in detail in Mackey et al.[5] Briefly, the method involves the following:

1. Estimates of eight long-term mean monthly climatic parameters were generated on a 1-km grid base across the entire province. The climatic parameters used were:

- Growing degree-days for Period 3 (total growing season) in °C;

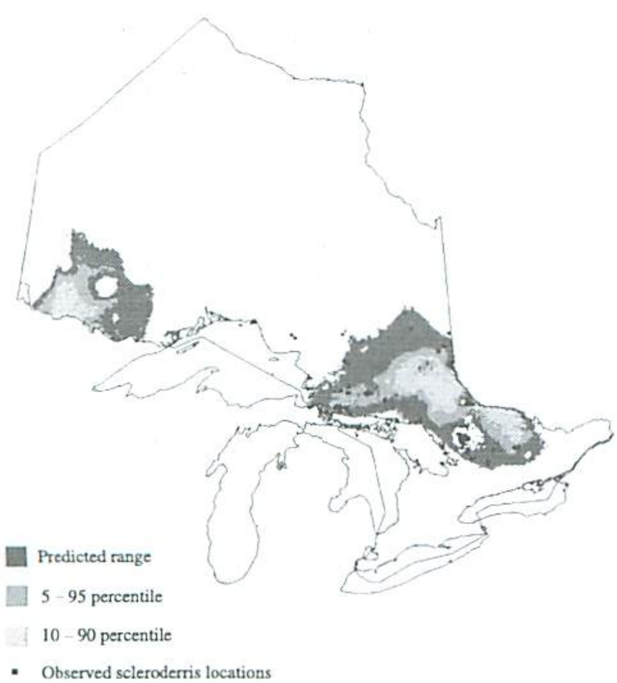

Figure 5. A climatic domain for red pine with scleroderris locations.

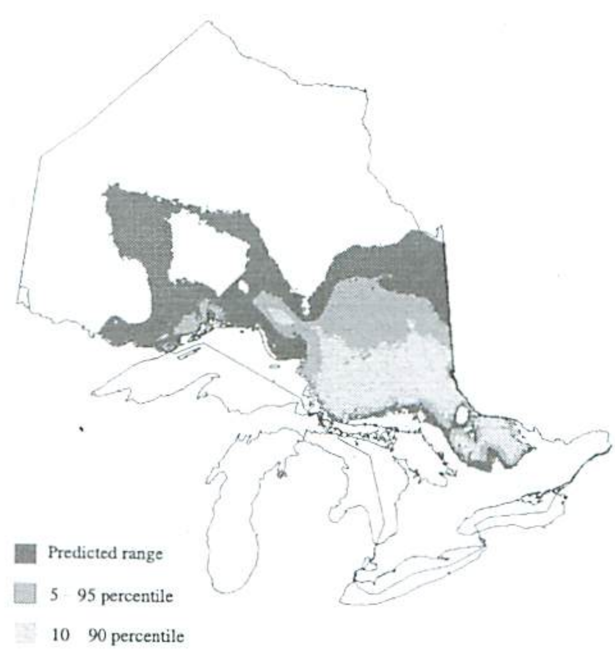

Figure 6. A preliminary climate domain for scleroderris canker.

[4] Mackey, B.G.; McKenney, D.W.; Yin-Qian, Y.; McMahon, J.P.; Hutchinson, M.F. Site regions revisited: A climate analysis of Hills' site regions for the province of Ontario using a parametric method. Canadian Journal of Forest Research. (In press.)
[5] Ibid.

- Total precipitation for Period 3 in mm;
- Total precipitation for Period 1 (3 months prior to growing season) in mm;
- Duration of growing season in days;
- Mean maximum temperature of the hottest month in °C;
- Mean minimum temperature of the coldest month in °C;
- Mean temperature of the hottest quarter in °C; and
- Mean precipitation of the hottest quarter in mm.

2. This data matrix of 756 104 grid cells x eight climatic variables was analyzed using the nonhierarchical, agglomerative classification procedure "ALOC", as found within the statistical package "PATN" (Belbin et al. 1993). This is essentially a clustering algorithm where cells are grouped on the basis that they share similar climatic values, rather than on the basis of geographic adjacency. Hence, cells can belong to the same group but occur as outliers within a region dominated by another group. This distinguishes the method from traditional climatic groupings, which commonly map homogeneous regions with no outliers.

3. In principle, any number of classes can be generated and mapped — from 1 (i.e., all grid cells allocated to a single climate class) to n (the number of grid cells). The optimum number of classes depends on the problem at hand.

Classifications generated using this method have advantages over the two-dimensional domain analysis discussed previously. As the multivariate analysis reduces all eight climatic variables into a single dimension, the geographic distributions of the climate classes can be readily mapped and visualized. The 14-group classifications were used here to analyze the data sets.

Table 2 displays the results of the EDIS analysis for the 14-group classification. Illustrated are the percent area, the total number and percent of plots, and a Plot Proportion Index (PPI) for each class. The areas for each class were derived from the grids used by the EDIS software. The PPI was calculated by dividing the percent plots by the percent area for each class. The PPI allows for a relative comparison of sampling between classes. When the PPI is near 1 the percent of plots is close to the percent area of the class. As the PPI approaches 0, this indicates that the class is not as well sampled as are classes that have a higher PPI.

The ARNEWS data set has the most representative sample, having plots in all but three classes (two of which are in the very far north). However, Class 9, which covers 14.3% of Ontario, has no plots located within it and should be considered in a future expansion. The scleroderris survey has plots well distributed across the classification. There are explainable gaps in representation in the most southern and northern regions of Ontario. However, Class 10, which lies within the distribution range of red pine (host tree species for scleroderris canker), is unsampled. Of the jack pine budworm survey plots, 61% are in Class 7 (PPI 10.2) and 26% are in Class 10 (PPI 3.6). Classes 3, 6, 9, 12, and part of 13 occur within the range for jack pine, but were not sampled.

DISCUSSION AND CONCLUDING COMMENTS

A major component of the Bio-environmental Indices Project (*see* Mackey and McKenney 1994) has been the establishment of high-resolution databases of environmental attributes and conditions across Ontario including variables for climate, terrain, and vegetation cover, together with spatial models of the potential distribution of a wide range of plant and animal species.

In this note, gridded estimates of long-term climate underpinned the analyses. Climate is a significant driving

Table 2. EDIS results using the 14-class climate classification.

Class/data set	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Percent area of class	2.9	3.6	2.9	3.4	4.3	2.4	6.0	12.2	14.3	7.4	3.1	12.5	15.1	9.5
ARNEWS														
Number of plots	2	3	5	3	6	3	3	3	0	6	3	1	0	0
Percent of plots	5.3	7.9	13.2	7.9	15.8	7.9	7.9	7.9	-	15.8	7.9	2.6	-	-
PPI*	1.8	2.2	4.6	2.3	3.7	3.3	1.3	0.6	-	2.1	2.5	0.2	-	-
Jack pine budworm														
Number of plots	0	15	0	0	80	0	637	30	0	274	5	0	0	0
Percent of plots	-	1.4	-	-	7.7	-	61.2	2.9	-	26.3	0.5	-	-	-
PPI	-	0.4	-	-	1.8	-	10.2	0.2	-	3.6	0.2	-	-	-
Scleroderris positive														
Number of plots	0	14	128	0	40	5	22	18	12	0	25	5	0	0
Percent of plots	-	5.1	47.0	-	14.7	1.8	8.0	6.6	4.4	-	9.2	1.8	-	-
PPI	-	1.4	16.2	-	3.4	0.8	1.3	0.5	0.3	-	3.0	0.1	-	-

* PPI = Plot Proportion Index. (See text for details.)

force determining the structure, composition, distribution, and productivity of plant and animal populations. Climatic regimes that are unsampled may indirectly reflect associations of unsampled flora and fauna. Undoubtedly, parts of the unrepresented climate regimes exist where it would not be possible to establish a forest survey plot. Such areas include agricultural land, forested private land, urban areas, and other nonforested land.

The next step in this work is to undertake analysis of the site data using inferential statistics to estimate the extent of correlation with climate. These relationships will be used as the basis for predictive spatial modeling. Satellite images could be used to further refine the spatial models by factoring in extant land cover and distances from roads. The approach described here could be used to stratify the province and assist in choosing future plot locations for particular biological questions. In addition, it provides opportunity to add value to historical biological databases. For example, the fact that particular climate domains appear "overrepresented" in jack pine budworm sampling could be taken as evidence that infestations of this pest are associated with that particular set of climatic parameters. This could be the starting point for a hazard-rating scheme for this pest. If statistical evidence is found, hypotheses could be developed and, using GIS databases, strategies for future plot locations could be established. This same approach could be used to address problems with scleroderris in red pine plantations. Forest health plots, such as ARNEWS, need to be as "representative" as possible to ensure that they capture the questions under investigation. In such cases, spatial data are required to objectively assess the adequacy of existing plots and to identify locations for new plots. Future work by the authors will also describe algorithms to identify representative points (potential plots) from gridded data.

In summary, a systematic, computer-based approach for stratifying the environment and identifying plot locations would be useful for several reasons:

1) Surveys could be designed to generate samples that are representative of relevant environmental gradients (e.g., climate).
2) It could help to develop a more systematic protocol for plot locations by providing objective guidelines to site selection. These could be modified as more knowledge is derived.
3) It would support the scientific analysis of plot data by, for example, helping to define the limits of inferences made from field plots.
4) It could be used in conjunction with historical survey data to generate testable hypotheses at the landscape level.

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