6.2 Design and Analysis for Detection Monitoring of Forest Health

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Summary

An analysis procedure is proposed for the sample design of the Forest Health Monitoring Program (FHM) in the United States. The procedure is intended to provide increased sensitivity to localized but potentially important changes in forest health by explicitly accounting for the spatial relationships between plots in the FHM design. After a series of median sweeps along axes of interest, the effect vectors and residual matrices are analyzed both statically and are carried through time to facilitate testing of postulated changes in forest health. A preliminary example is given utilizing FHM data from New England for a single time period.

Keywords: forest health, forest damage, spatial statistics

6.2.1 Introduction

It is the goal of the detection monitoring phase of the Forest Health Monitoring (FHM) Program in the United States to be able to detect changes in the forest condition which might be considered harbingers of serious forest health problems. The mechanism through which this detection is to be achieved is the monitoring of variables which would theoretically indicate a change in forest health. The achievement of this goal requires an analytical approach somewhat different from those traditionally found in the forestry literature. We can recognize this if we think about the fairly well established ecological principle that stressors affect species at the limits of their ranges first. If we want to detect the early symptoms of stress we have to pay attention to very localized changes, perhaps even to the extent of treating each measured plot as a unique entity, at least at the outset.

Our goal necessitates the question: What constitutes a sufficiently general sample design and analysis to detect harbingers of deleterious changes in forest health? A satisfactory sample design would conform to some minimum requirements. It would either afford complete coverage of the population of interest or, if the sampled population is different from the population of interest, the difference must be shown to be negligible. The sample design would incorporate some mechanism to divide each population into mutually exclusive units which are selected from with known probability.

Complete coverage of the population of interest requires a minimally sufficient dimensionality to the design. A minimally sufficient dimensionality for a forest health monitoring design would include the four dimensions of latitude, longitude, elevation and time. Since elevation is implicitly sampled by explicit sampling of longitude and latitude, it is usually assumed that elevation can be ignored in design description.

Once the design is established there are many alternative analytical treatments of this dimensionality. One could ignore the fact that the data came from a spatially correlated system by treating the data as if they were independently derived. This is the usual approach in forestry, and is warranted by the usual intensive nature of forestry investigations. If, on the other hand, the survey is to be extensive as it is for the FHM Program, then some accounting for differences due to spatial position is necessary. Along these lines we could fully analyze the effect of all of the spatial dimensions or we could implicitly undermine the importance of one (or more) of the dimensions by collapsing it down into the remaining dimensions (as we will usually do for elevation).

6.2.2 **The FHM Design Genesis**

From the outset, it was argued within the FHM Program that FHM should remain separate from the USDA Forest Service's Forest Inventory and Analysis (FIA) survey and the National Forest Surveys (NFS). This argument stemmed, in part, from the recognition that within the forestry profession unofficial standards, e.g. measuring height to the nearest foot and DBH to the nearest 1/10 inch, have evolved through the decades which may not be applicable to the goal of monitoring forest health. These standards have evolved and become somewhat built into both the FIA and NFS surveys because they are quite appropriate for the original goals of those surveys, that of describing the general state of the timber supply in the forests of the United States and on the National Forests respectively. Some of these standards may be too coarse for FHM in that the measurement error may be larger than the scale of detection. In addition, FIA surveys are only repeated every 7 to 13 years, depending on the state. This time scale is too coarse for the early detection of changes in forest health. Objection to the incorporation of FHM into FIA on these grounds is misguided. FIA and all forest survey organizations change standards as those changes become necessary and advantageous to the goals of the survey. In addition, even though measurement standards may be coarser in past FIA inventories, the decades of information collected during the FIA and NFS surveys could still be used to form baselines from which to monitor changes in variables related to forest health.

One quite valid objection to the use of FIA and survey plots for FHM raised by some of the FIA project leaders was that the greater frequency of plot visits (originally proposed as 1 per year) would tend to affect FIA's ability to obtain landowner permission to access the plots. This might jeopardize access to plots which have already been measured for a long time and are considered quite valuable. On the other hand the same reasons that make these long-standing plots valuable to the goals of FIA also make them valuable to FHM. In addition, the increased spatial density of the FIA grid would be extremely valuable to FHM.

In this regard, a recent positive change has occurred for FHM's 1994 field season in that the North Central Forest Experiment Station has agreed to overlay FHM plots onto FIA plots in Minnesota and possibly the other north central states.[1] The potential advantages of this change are discussed below.

6.2.3 **The FHM Design**

The FHM design actually varies slightly by region and state but in general it consists of a randomly placed triangular grid covering the United States. The placement of the grid was accomplished by arbitrarily positioning an enclosing hexagon (which I will call HEX1) over the map of the contiguous 48 states, as in Figure 1. HEX1 was then partitioned into approximately 28000 smaller hexagons of 635 km^2 (each an individual HEX2). A point was randomly selected to occupy the same position within each HEX2 to form the triangular grid. From each point of the triangular grid the nearest FIA photo point within HEX2 is

[1] FHM/FIA meeting, December 6-7, 1993; NC Forest Experiment Station, St. Paul, MN.

chosen for a sample point (in some cases something other than FIA photo points are used). If the photo point is classified as something other than forest no variables are measured. If the photo point is classified as forest but landowner permission to access the plot is denied, the next closest photo point becomes the plot location. Note that this design chooses a single cluster sample of photo points which currently correspond to approximately 4500 forested plots (SCOTT et al. 1993). I will ignore the landowner permission problem in the sequel. A time interpenetrating feature has been proposed and may be incorporated into the design where each year one-fourth of the plots will be measured in a repeating systematic pattern as shown in Figure 2.

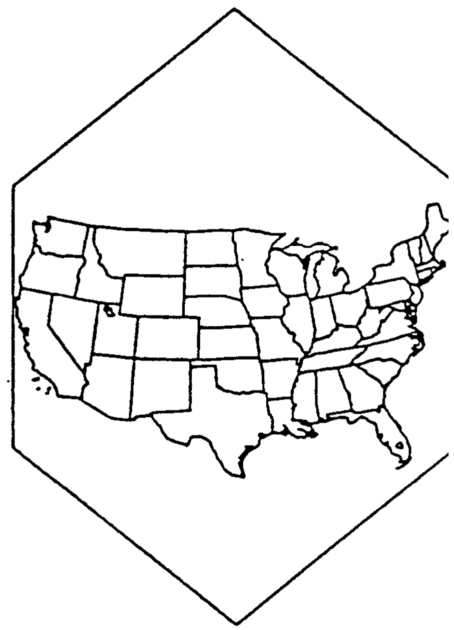

Fig. 1. The contiguous 48 states of the United States with an enclosing hexagon (as an example of HEX1 in the text).

The design minus the FIA/FHM overlay feature mentioned above has both advantages and disadvantages for the purpose of monitoring forest health.

Some design weaknesses are:

1) There is no reliable variance estimator;
2) There is no mechanism to preclude the confounding of space and time in the proposed interpenetrating feature;
3) It is less efficient than the design which would have resulted from an assumed integration with FIA and NFS plots, because the latter design could have gained a spatial advantage from the FIA and NFS plots and a temporal advantage from FHM plots;
4) The triangular grid is closely aligned with major ecological systems- i.e. the NE/SW orientation of the Appalachian Mountains in the eastern United States.

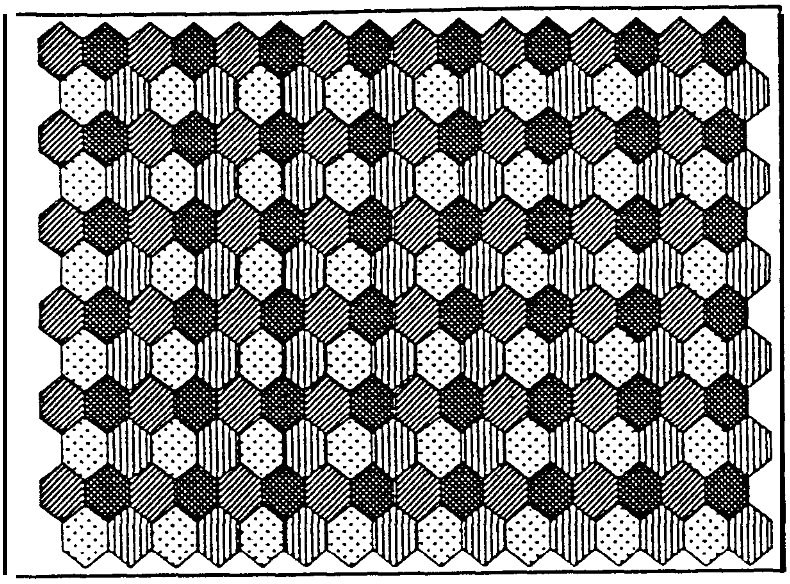

Fig. 2. The interpenetrating feature. Plots in HEX2's of the same pattern will be measured during the same year on a four-year rotation.

The major strength of the design is that the regular grid spacing provides highly efficient coverage of the land area. If the time interpenetrating feature is incorporated it will save money and lessen the potential for visit effects such as trampling at a cost of a reduced temporal measurement intensity coupled with the introduction of a spatial/temporal confounding.

When discussing a sample design, we could work from either design-based sampling theory or model-based sampling theory or perhaps some hybrid of the two. The FIA/NFS photo points could be viewed as a finite set of points drawn from an infinite number of possible sets of points (known as the super population model). A cluster sample of size 1 is then selected from this given set of photo points. In this case the cluster is chosen with a probability not equal to the probabilities of the other clusters which might have been chosen from this particular set of points. This is because the triangular FHM grid selects the photo points which are not evenly spaced across the country or even within a region. To show that undue concern with these unequal probabilities is unnecessary, I will initially exploit an idea outlined in ROESCH et al. (1993) called the jigsaw puzzle view of forest sampling.

To visualize the conditional probability of selection of a particular cluster given the particular set of photo points, picture the outlined areas from within which each of the FIA photo points would be selected. Then overlay the HEX2's described above on this map of outlined selection areas. Now cut out the overlaid layers according to the HEX2 map and lay the 28,000 HEX2/FIA outlines directly on top of one another. Now select all of the photo points at once by dropping a perpendicular ray through the stack and picking the point corresponding to the area through which the ray travels in each HEX2. The probability of a particular cluster of points being chosen is equal to the intersection of the outlined areas (looking from the top of the stack) from within which each of the chosen photo points could be selected divided by the area of HEX2. That this joint probability is the conditional probability of interest is obvious in light of a basic tenet of probability theory which recognizes that any 1 random event has exactly 1 outcome. Typically, in forestry, the individual ground plots are subsequently treated as having been selected independently for purposes of obtaining an estimate of variance. This results in a conservatively biased estimate of variance.

Even though the FIA photo points are selected as a cluster, each possible FIA photo point does have an individual probability of selection which could be calculated. Due to an elaborate effort within the FHM Program to calculate these probabilities, the consequences of this unequal probability sample of FIA photo points bears mention. It is neither wise nor necessary to use these probabilities for estimation. It is not wise for a number of reasons, the most compelling of which is that the exact location of each FIA photo point has nothing to do with the population of interest. We want to make inferences on the land area through time, not on the set of FIA photo points. The probability of real interest is the probability of having selected a particular cluster of sample points from the infinite set of sample points over the entire land area. This probability is zero because the probability of selecting a particular individual from an infinite population is zero. It is an unconditional probability as opposed to the probability conditional on the particular set of points which happened to become FIA photo points. Note, in addition, that there is no reason to favor the estimate for one HEX2 over that of another, which would be the result of the inappropriate use of these conditional probabilities. Because the conditional probabilities have nothing to do with the population, ignoring the differences in these conditional probabilities of inclusion is not likely to introduce a bias while using these conditional probabilities is likely to increase variance in the estimates. The nuances of weighting sample realizations by probabilities of inclusion are thoroughly discussed, in KISH (1965).

Even if one misplaces faith in these conditional probabilities, their calculation becomes unimportant when one acknowledges that the sample size is actually 1. This is because the weight applied to unit k in unequal probability sampling is equal to 1/z where $z = p_k*(\sum_i(1/p_i))$ (with i ranging from 1 to the sample size), which is equal to 1 when the sample size is 1. For example, an estimate of the total attribute X for the population could be obtained by $X_{est}=(A/a_p)\ \sum_i(x_i/p_i)/(\sum_i(1/p_i))$, where A is the area of HEX2 (635 km^2), a_p is the plot area (1/6 acre) and x_i is the total attribute measured for cluster i. Since the sample size is 1, X_{est} reduces to $(A/a_p)x_i$. Given that sampling theory provides no reliable estimator of variance for a systematic sample, one might be tempted treat each HEX2 as a sample unit and use the estimator of variance from simple random sampling. This estimator is conservatively biased in this case, as mentioned above. However, it is also not appropriate to use the conditional probabilities of inclusion corresponding to selection of individual FIA points (from the given set of FIA photo points) to calculate variance for the same reasons stated above. This corresponds to a stratified sample with each HEX2 being a stratum or to the combination of estimates from many populations, with each HEX2 being a population. Since the strata (or populations) are given the same sampling intensity of 1 plot each, the HEX2's would be weighted equally after a statistic such as the total or mean is obtained for each HEX2. To calculate a statistic for each HEX2, the chosen plot within each HEX2 would have a single p_i which again would be divided by itself to form the unequal probability sampling weight (obviously still = 1). That is, an estimator for the total over all the HEX2's would be $X_{es2} = \sum_k((A/a_p)(x_{ki}/p_{ki})/(\sum_l(1/p_{li})))$, where x_{ki} is the measured attribute on plot i in HEX2 k, and p_{ki} is the probability of choosing photo point i in HEX2 k. Since A and a_p are constants and $n = 1$, A and a_p can be pulled out of the summation, and we see that X_{est} equals X_{es2}. More importantly, neither estimator requires actual calculation of the sample probabilities.

One proposed view of the FHM sample design has caused unnecessary problems and ambiguities. This is the view of a two stage sample where instead of a point being selected initially to occupy the same position within each HEX2, a smaller fixed-area hexagon of 40 km^2 (HEX3) is randomly located to occupy the same position within each HEX2. HEX3 is characterized on a landscape scale and a subsample (presumably stage 2) of HEX3 chosen by locating a ground plot at the closest FIA point to the center of and within each HEX3. This view requires that there actually is an FIA photo point within HEX3. It has been found that this is not always the case and different ad hoc procedures have been used to then locate a point within HEX3. The restriction that the photo point must be within HEX3 is both unnecessary and inefficient. Given that HEX3 is intended to represent HEX2 in the first place, there is no reason to favor a location of the ground plot within HEX3 over a location somewhere else within HEX2, say at the closest FIA photo point to the center of HEX3. That is, HEX3 and the ground plot are really just two different kinds of samples of size 1 from HEX2.

Whether one views the FHM design as a cluster sample of plots (with 1 cluster being sampled consisting of one plot from each HEX2) or as a sample of size 1 from each HEX2, the same conclusion is reached: the probabilities of selection of the photo points conditional on the given set of photo points are irrelevant with respect to estimation, since the corresponding weight is always 1.

6.2.4 Analysis

Given that the FHM program is still in its infancy with respect to the monitoring of changes in forest health, I am only suggesting an approach to the analysis of FHM data, rather than attempting an actual analysis. An ideal analysis of this data would consider the spatial relationships of the individual plot values since autocorrelation may be present for many of the variables of interest, and indeed a change in forest health is likely to be localized, at least initially. For this reason, the goal of early detection would benefit from'a spatial analysis. The analysis I propose yields estimates of effects along axes of interest and an overall effect while preserving spatial identity in the form of a matrix of residuals, all of which can be carried through time. The overriding advantage of the median polish technique used below is that the effects are usually obtained without incorporating an undue influence from the outliers present. This leaves the outliers intact in the residuals, which is an advantage because the outliers may very well be the values of most interest. The exception to this occurs when too few observations exist in a particular row or column. The algorithm for the analysis is:

1) *At each point in time:*

A) Arrange the plot values by their associated triangular grid points (HEX2 centers), or possibly by collection centers after performing a coarse. mapping. A coarse mapping is accomplished by segmenting an area with a specific size grid and pooling the plots within each segment (e.g. see CRESSIE, 1991). Then

B) perform a 2-way median polish along two axes of interest (say latitude and longitude) and analyze the effect vectors, possibly by using a Bayesian trend analysis such as the one found in VAN DEUSEN (1994).

C) Optionally, one could perform another 2-way median polish of the residuals along 2 other axes of interest (say roughly in the NE/SW and NW/SE directions).

2) Over *the time series:*

A) Analyze the collected effect vectors for changes in distribution, perhaps again using a Bayesian trend analysis such as an extension of the one mentioned above by VAN DEUSEN (1994) to a third dimension. Finally

B) treat the final residuals as an independent data set of time-series observations, or look for further spatial correlations.

In addition I would incorporate applicable FIA and NFS data in one of two ways, depending on the variable. Variables measured by the same standards in all three systems should be averaged within the HEX2's, again corresponding to a coarse mapping, during a given year and then treated exactly as described above for the FHM data. For variables collected by different standards:

1) Use step l(A) above for the FIA and NFS data and take the average of all FIA/NFS plots within each HEX2;
2) Combine FIA, NFS and FHM as independent data sets and continue with the remaining steps above.

Pertinent questions that will have to be addressed by the analyst for a particular case include:

1) How coarse or fine should the mapping be?, and
2) If measurement standards are different, how should the data sets be combined?

The optimal solution to question (1) would result in a map which was fine enough to still display all of the important spatial trends and coarse enough to combine homogenous areas and eliminate as many “strays” from the 2-way table as possible. A stray is a datum which is the sole contributor to an element of one of the effect vectors. The best guidance to a solution to question (2) is found in the Bayesian literature (e.g. BERGER 1985).

6.2.5 **Example**

In this example, I use data from the 1992 FHM plots in New England. I calculate the percent of total basal area in spruce (*Picea* sp.) and fir (*Abies* sp.) trees for each plot. A single time period suffices to demonstrate the effectiveness of the median polish technique for analyzing the FHM data. Figure 3(a) shows the percent of the total basal area which is due to spruce and fir for each plot by latitude and longitude.

Note that if we made the mapping as fine as possible using the exact location of each plot (say to 1 minute of latitude and longitude) then the median polish technique would usually be using only 1 or 2 plots for each marginal. This is alleviated by collecting the plot information to the center of the HEX2 represented by the plot. Strays can create a problem in the analysis because they can give the appearance of an effect in the effect vectors even though one does not exist. A coarse mapping was performed to pool neighboring plots and further reduce the number of strays. Figure 3(b) shows the percent spruce/fir after a coarse mapping by 1/2 degree in both longitude and latitude. That is, the HEX2 centers which occupied common segments of a 30 minute longitude by 30 minute latitude grid were pooled.

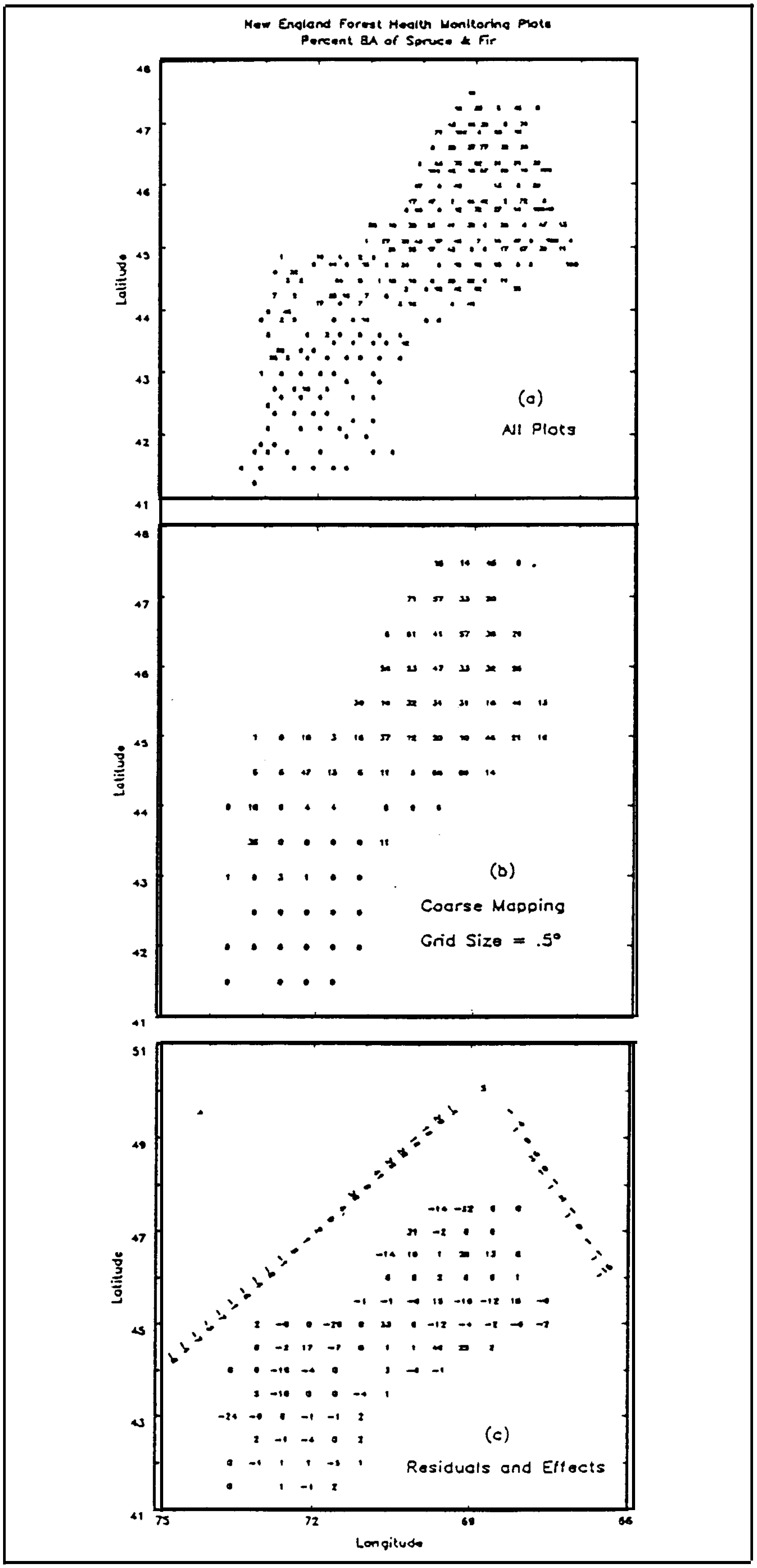

Fig. 3. The percent of basal area in spruce and fir: (a) by plot, (b) after plots are pooled following a coarse mapping of 0.5" in both longitude and latitude, (c) the residuals and effects (diagonal and total).

In consideration of what we know about the distribution of the spruce/fir type in New England, say as collected in BURNS and HONKALA (1990), it is of interest to examine effects along the diagonal axes (that is the NE/SW and NW/SE axes). Figure 3(c) shows the results of performing median sweeps along the diagonals. Since land types run in roughly a northeast to southwest direction in New England the NE/SW and NW/SE effect vectors are of particular interest. One could for instance postulate that a change in forest health might be detectable by analyzing change in the NW/SE effect vector of percent basal area in spruce and fir through time (the vector in the upper left part of Figure 3 (c)). This is likely to be an effective indicator of health because there is a noticeable trend in the vector initially (save for the "stray" effect at the top of the vector) and threats to the health of a population are usually first noticeable at the extremes of the area1 range of the population.

The pattern of the NE/SW effect vector (vector at upper right of Figure 3(c)) corresponds roughly to the elevation gradient in New England, reflecting the noted affinity for cool, moist climates by the spruce/fir complex in general. The "total" effect at the intersection of the two diagonal effect vectors in Figure 3(c) is only meaningful once an adequate time series has accumulated to test for overall trends in the proportion of basal area in spruce and fir.

This example has shown the use of the median polish technique subsequent to a coarse mapping for data summarization of a forest monitoring variable. It has resulted in a fairly good picture of the current state of the variable which can be carried through time to monitor changes in the variable. In the future if it is decided that a different coarse mapping should be used (say the one considering individual HEX2's), one can simply apply the same process with the alternative size mapping grid to the accumulated raw data.

6.2.6 **Acknowledgement**

The Forest Health Monitoring data were provided by Charles Barnett and Andrew Gillespie of the USDA Forest Service Northeastern Forest Experiment Station, Forest Monitoring Program.

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