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DESIGN AND ESTIMATION FOR INVESTIGATING THE DYNAMICS OF NATURAL RESOURCES

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Abstract. Federal agencies, policy makers, and scientists have long been interested in monitoring natural resources and environmental conditions on a national and regional scale. One of the main objectives of these studies is to estimate temporal changes in the extent and condition of natural resources. In its simplest form, temporal change can be defined as the difference between population parameter values at two time points for a given population. A more complex investigation of change in an ecological system involves studying the underlying dynamics that produce an observed net change. We discuss the general problem of sample design and statistical estimation to support investigations of the dynamics of change in ecological systems, particularly when a limited number of temporal observations are available. We focus on large-scale natural resource monitoring surveys through the example provided by the National Resources Inventory (NRI), a longitudinal survey conducted by the U.S. Department of Agriculture (USDA). Sample design, data collection, and statistical methods for constructing an accessible database are outlined, with emphasis on features that support investigations concerned with temporal dynamics. An example from the 1992 NRI is presented to illustrate methods for investigating temporal changes in land use in relation to observed changes in erosion rates over time. Finally, we discuss how statistical methods developed for the NRI program can be applied more broadly to environmental monitoring studies.

Key words: environmental monitoring; environmental statistics; multi-stage design; survey sampling; two-phase estimation.

Introduction

Federal agencies, policy makers, and scientists have long been interested in monitoring status and trends for natural resources on a national and regional scale. To support such investigations, the federal government has implemented several large-scale monitoring efforts over the years, including the U.S. Forest Service's Forest Inventory and Analysis program (Scott 1998), U.S. Geological Survey's National Water Quality Assessment programs, and the U.S. Department of Agriculture's National Resources Inventory. Each program has developed a unique design and estimation approach to address its monitoring objectives and operational constraints. In this paper, we examine the topic of change and trend detection for ecological monitoring studies in relation to large-scale natural resource surveys that include a monitoring component.

It is useful to consider aspects of temporal trends that might be of interest in ecological systems. In its simplest form, ''temporal change'' can be defined as the difference between population parameter values at two time points for a given population. Examples of parameters include mean chemical concentrations in a stream, total area in a specific land use, surface area of farmland devoted to a particular agricultural practice, or a percentile from a distribution of contaminant concentrations. The population may be a geographic region, a species or ecological assemblage, or a collection of specific land covers such as wetlands or forests. A more complex approach to studying temporal change is to investigate the underlying dynamics that produce an observed net change in an ecological system. For example, a net decline in surface area suitable for wildlife habitat in a region may result from an increase in idled cropland enrolled in the Conservation Reserve Program coupled with a loss of habitat due to urbanization. In order to pursue this approach, a study must be carefully designed so that data are collected that reveal patterns underlying observed temporal changes.

The purpose of this paper is to discuss statistical design and estimation for investigations of the dynamics of change in ecological systems. We focus in particular on survey sampling methods for large-scale natural resource monitoring surveys, with illustrations from the U.S. Department of Agriculture's Natural Resources Inventory (NRI). The general approach is to collect data on a suite of variables from repeated ob-

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servations on sample units selected from the region of interest. A component of the sample design includes sample points, so that specific patterns of change in response variables can be tracked in relation to related factors. The underlying factors can frequently be formulated into a sequence of ''states'' that describe the history of conditions at a point. Tabular or graphical summaries can be used to summarize the extent (e.g., surface area) of specific temporal change patterns in the population as well as responses to the patterns.

In what follows, a brief introduction to survey sampling is provided. The sample design of the NRI is outlined with emphasis on features that support investigations concerned with temporal dynamics. Data collection is briefly described, and statistical procedures suitable for constructing a longitudinal database for trend analysis are discussed. We present an example of analyses to investigate the dynamics of observed changes in erosion rates over time, and methods for displaying erosion dynamics in relation to land use and cropping practices. Finally, we discuss how statistical methods developed for the NRI program can be applied more broadly to environmental monitoring studies.

Fundamentals of Survey Sampling

Most well-designed scientific studies involve selecting a random sample from a defined target population, observing data on the sample units, and analyzing sample data to make inferences about the entire target population. The statistical methods used in many areas of scientific inquiry are developed for infinite populations (e.g., experimental design, ANOVAs), and analyses frequently require distributional assumptions to develop estimators of population parameters. In contrast, survey sampling involves selecting random samples from a finite population using a specified sampling design. Cochran (1977) is a standard reference. The population can be thought of as a finite list of units or *elements.* Samples are selected from a list referred to as the *sampling frame,* which to the extent possible, covers the elements in the population.

Sample designs used to select elements from the sampling frame are based on structures similar to those used in experimental design for infinite populations. For example, simple random samples from finite populations are analogous to completely randomized designs. Stratified samples involve dividing the population into mutually exclusive groups of elements called *strata,* and selecting independent random samples from within each stratum. When simple random sampling is used within strata, stratified samples are similar to randomized complete block designs. As with blocked designs, stratification is used to insure that the sample is spread across the full range of conditions in the population. Stratification is also used to insure adequate sample sizes for populations, to implement varying sample designs across subpopulations, and to facilitate operational considerations. A more elaborate design is two-stage cluster sampling, which involves selecting groups of population elements, called *clusters* or *primary sampling units* (PSUs), during the first stage of sampling, and subsequently selecting a subsample of elements from each PSU as the second stage of sampling. Two-stage cluster samples have a structure similar to that of split-plot or nested designs. Cluster sampling is frequently used to improve operational efficiency because it can be used to select sets of sample units that are proximal. Two-stage (or multi-stage when more than two stages are used) cluster samples involve different kinds of sampling units at each stage, and thus also enable information to be gathered on different kinds of population elements. In natural resource surveys, for example, there may be interest in measuring areas within polygons of land (PSUs) at stage one, and in recording categorical or continuous measurements at specific point locations within PSUs at stage two. Another type of design is two- (or multi-) phase sampling. A sample of elements is selected in the first phase, usually to collect data on variables that are relatively simple or cheap to observe. The second phase typically involves selecting a subsample from the first sample, and collecting intensive observations. The two sets of information collected during the two phases are combined during the estimation process. When first- and second-phase variables are highly correlated, this design provides an effective method of compensating for the small sample sizes that can result from collecting expensive data with limited resources. In practice, there are many variations to each type of survey sample design, and these design structures are frequently combined in developing complicated sample designs. For example, one of the most common designs in federal survey programs is stratified multi-stage sampling. Subsamples may be selected from such a design as a second-phase sample to conduct a special investigation, where the original sample or database plays the role of the first-phase sample.

Classical survey sampling estimators for population parameters are derived from the properties of the sample design, much as randomization tests are derived in experimental design. These estimators are often referred to as *design-based* estimators, and typically have the form of $\Sigma_{i \in A} w_i y_i$, where y_i is the variable of interest for selected element i, w_i is the *sample weight,* and A is the set of labels for elements contained in the sample. In its simplest form, the sample weight is the inverse of the probability of the element being included in the sample; this probability is called the *inclusion* or *selection probability.* The weight is essentially a measure of how many elements in the population are represented by the sample element. A more complicated weight incorporates existing information on the size of the population (*control* information) to ''calibrate'' the weights so that the estimators produce results consis-

tent with known population parameters. In particular, known surface areas can be used as control totals in surveys of the land, so that the sum of the weights for sample units in, for example, a state is equal to the known surface area of the state as published by the Census Bureau. *Model-assisted* estimators combine design-based information with a model-based component to incorporate other kinds of auxiliary information as a means of improving the properties of the estimator (Särndal et al. 1992). For example, in estimating changes in the extent of urban surface area over time, human population figures for the urban area could be used as auxiliary information.

Because the sample is selected from a finite sampling frame, variance estimators differ from those associated with experimental designs for infinite populations. In particular, standard survey sample variance estimators include a finite population correction term, which is a function of the fraction of population elements sampled. For example, for a simple random sample of size n from a population of size N, an unbiased estimator of the variance of the sample mean is

$$\left(1 - \frac{n}{N}\right)\frac{s^2}{n}$$

where

$$s^2 = (n - 1)^{-1} \sum_{i \in A} (y_i - \bar{y})^2$$

$$\bar{y} = n^{-1} \sum_{i \in A} y_i$$

and A is the sample label set.

Finally, we note that in survey samples, data are collected on *reporting units.* Reporting units are frequently defined to be a sample unit. However, reporting and sampling units may differ. For example, the sample unit may be a point on the land, but a two-dimensional plot centered at the sample point may be used to observe data. Reporting units for control information used in estimation typically represent mutually exclusive and exhaustive units that cover the population, and may not be formally associated with a sample unit during the data collection phase.

Although survey sampling is frequently recognized as an approach used to conduct studies of human populations, survey sampling methodology is used in numerous federal surveys of agricultural production and natural resources. In this paper, we consider finite populations defined by land areas, such as political or ecological regions. Sample units correspond to polygons of land, called *area segments,* or to specific point locations. The ecological population of interest (e.g., all forest land, an animal or plant species) may be contained within the finite population used to select a sample (e.g., all U.S. lands, a region of the United States). When area segments are used as sample units, the sample is called an *area sample.* One of the advantages of using area samples is that the sampling frame, which can be thought of as a list of area segments, can usually be constructed to cover the entire population of interest. Weights for area samples are generally expressed in units of area, such as hectares or acres, and may be a function of known surface areas within polygons, such as the surface area of states or hydrologic regions. When developing a sample survey to support monitoring objectives, the sample must be carefully designed to meet analysis objectives. In particular, in order to obtain precise information on the dynamics of change, a component of the sample design must include repeated visits to sample points. Other sampling units, such as area segments, may be used to detect rare patterns and to provide data that can be used to improve the properties of sample weights. To illustrate the application of sampling to natural resource surveys, we begin by briefly describing the sample design, data collection, estimation, and weighting procedures used to create the longitudinal database for the 1992 NRI.

The National Resources Inventory

Overview

The National Resources Inventory (NRI) is a longitudinal survey conducted by the USDA Natural Resources Conservation Service (NRCS, formerly the Soil Conservation Service) in cooperation with the Iowa State University Statistical Laboratory. In its current form, the NRI is designed to assess conditions and trends at 5-yr intervals for soil, water, and related natural resources on nonfederal rural lands of the United States. The survey has evolved over a period of several decades, with the specific goal of providing monitoring and status information to support policy development and program implementation for conserving natural resources. The most recently produced data set contains data corresponding to 1982, 1987, and 1992 conditions on each of ~800 000 sample points throughout the United States (Kellogg et al. 1994, USDA 1994). Data were collected on agricultural variables such as land use patterns, soil types, soil properties, soil erosion, conservation practices, rangeland quality, and conversion of prime farmland to nonfarm uses, as well as on ecological characteristics such as wetlands, habitat diversity, and vegetative cover. Data on 1997 conditions are being gathered on the same set of sample units as part of the 1997 NRI.

Sample design

The sample design for the 1982, 1987, and 1992 NRI survey series was developed to address several requirements, including broad geographic spread of the sample, the need to estimate change over time, and the ability to vary sampling intensity over geographic areas and land use categories in order to achieve adequate sample sizes for subpopulations and manage operational resources. The NRI sample design is based on a

stratified two-stage area sample of all U.S. lands. Design features include numerous small strata covering U.S. lands, small area segments or PSUs selected within strata, and selection of 1–3 points within each PSU during the second stage of sampling. Longitudinal aspects of the design involve observing conditions at the same sample units over the course of the survey series. Details of the 1992 sample design are provided in Nusser and Goebel (1997), along with information on the historical evolution of this design. Below we focus on describing major features of the 1992 design and how they act to support study objectives.

Stratification is used in the NRI to achieve geographic spread, to help manage operational aspects of data collection, and to provide a mechanism for varying sample sizes in relation to survey objectives and heterogeneity of natural resource conditions. Strata are defined by small political (subtownship or parish) or geographic (polygons defined by geographic coordinates) units. In most states, a stratum is 3.22 × 9.66 km (2 × 12 miles), or ~3110 ha. Fig. 1a illustrates a typical stratum for Public Land Survey counties and its relation to political boundaries. The advantage of using political or geographic units to define strata for longitudinal surveys, rather than natural resource groupings, is that the boundaries are well defined, widely recognizable, and likely to remain constant over time. Because NRCS, the agency administrating the survey, is organized according to political boundaries (e.g., state offices), using political structures for strata also makes it simpler to allocate sample sizes in relation to agency resources for the political units. By subdividing the U.S. surface area into tens of thousands of small strata, excellent geographic spread is achieved. In addition, this configuration of strata forms a flexible basis for defining the boundaries for many types of subpopulations, even if the subpopulation boundaries change over time.

The first-stage or primary sampling units (PSUs) are area segments. They are relatively small, typically 0.80 km (0.5 miles) on a side, or ~64 ha (Fig. 1a). PSUs are also defined by political (quarter section) or geographic (latitude, longitude) boundaries. The small size makes it possible to accurately enumerate measurements such as land areas within the PSU. Previous studies indicate that for NRI, where detailed photo-interpretation materials or field visits are required, data collection for larger sample units are subject to sizable measurement error and are operationally inefficient. Depending on the desired sampling density, 1–4 PSUs were selected from within each stratum. The procedure used to select PSUs involved restricted randomization to encourage geographic spread within each stratum. The 1992 NRI sample contains ~300 000 PSUs. The primary sampling rates generally range from 2 to 6% of the land area, though rates occasionally fall outside this range. The sampling rate within a county is increased when larger sample sizes are needed for special studies, or when heterogeneous patterns exist for soil types, land uses, major land resource areas (MLRAs; see USDA 1981), or hydrologic regions. Fig. 1b shows the density of PSUs in Iowa, including a denser county-level sample in the southeast portion of the state, and a denser sample in the northwest corner to achieve sample size requirements for an MLRA that crosses into other states.

In the second stage of sampling, a small number of sample points, usually three, were selected within each PSU according to a restricted randomization procedure that encourages geographic spread among the points (Goebel and Baker 1992). Once again, sample size for secondary units within PSUs was determined by studying the balance of operational constraints, measurement errors, and statistical efficiency for various second-stage sample sizes. Data were collected for ~800 000 points during the 1992 NRI.

Like most monitoring studies, the NRI is designed to estimate status at a particular time point as well as to estimate changes in status over time. Longitudinal aspects of the NRI are based on repeated observations on sample PSUs and points. As noted earlier, repeated point observations are essential to obtaining specific information on changes in conditions and response variables over time. Each sample unit included in the 1992 database has a series of observations corresponding to 1982, 1987, and 1992 growing season conditions. 1997 NRI data are being collected for all 1992 sample units.

Data collection

During the 1992 NRI, data were collected for the 1992 growing season on three different types of reporting units: sample points, sample PSUs, and polygons defined by the intersection of MLRAs and counties (called MLRACs). A wide range of variables, or *data elements*, were included to address survey objectives and to provide information to support estimation. Data collection was based mainly on photo-interpretation and auxiliary supporting materials such as conservation plans and soil maps. A small portion of the sample units were field-visited for special studies or when photographic materials were inadequate.

The majority of the data elements were collected at the sample point. Point data elements mainly consisted of variables designed to address analysis objectives, including land use and land cover, soil type and properties, factors used to estimate soil erosion, irrigation, highly erodible land classification, cropping history, conservation practices, potential for conversion to cropland, vegetative cover, distance to wildlife habitat, wetland classifications, and a number of condition-related factors for rangeland. Definitions for data elements and procedures for data gathering are explained

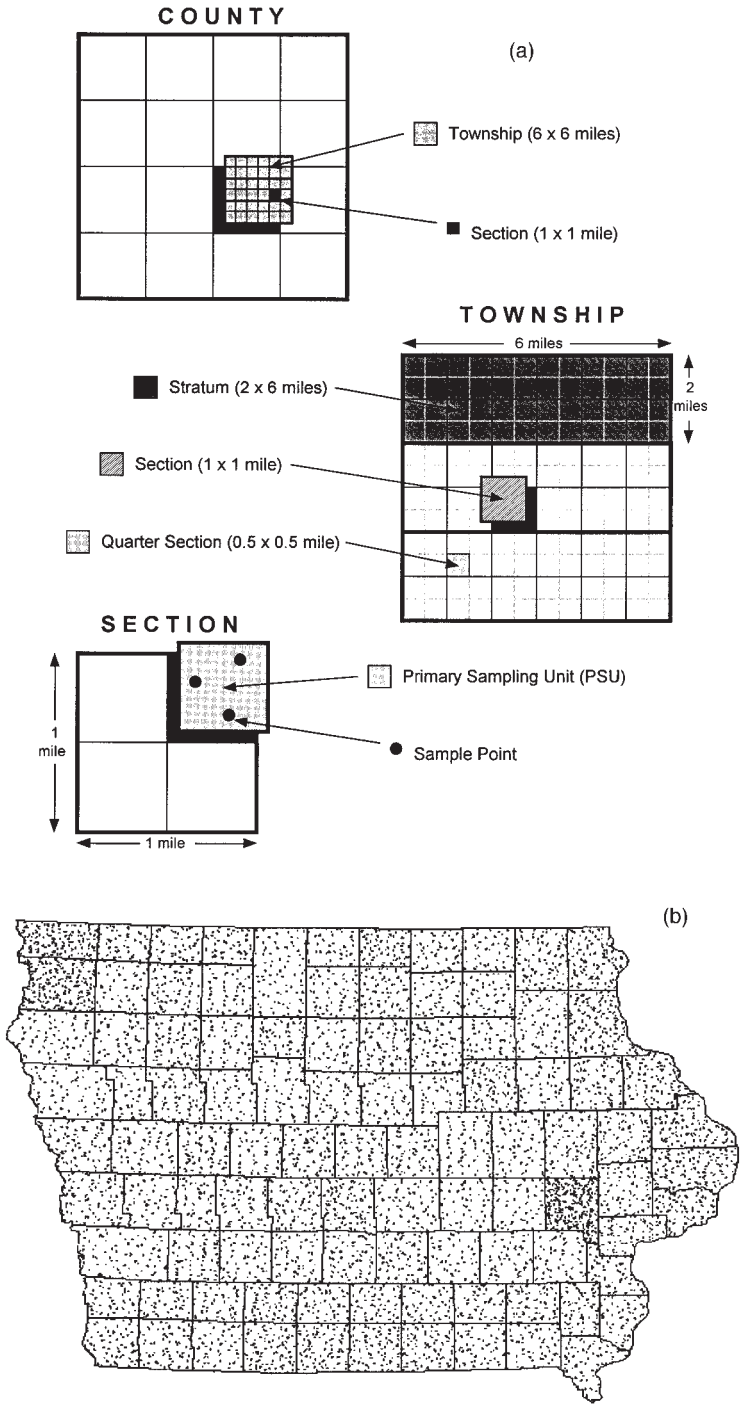

FIG. 1. (a) A graphical representation of the political subdivisions of a typical Public Land Survey (PLS) county, and the relationship of PLS subdivisions to a typical NRI stratum, first-stage or primary sampling unit (PSU), and second-stage sample points. (b) A representation of the 1992 NRI PSU sample for Iowa.

in detail in the 1992 NRI instruction manual (USDA 1991).

For each PSU, surface area data were collected for several land use categories. These variables included surface areas for selected land cover/uses and ownership categories, classification variables for MLRA and hydrologic unit, and some climate factors that serve as input for point-level erosion calculations. As will be seen in the next section, these variables were used as control information in conjunction with PSU inclusion

probabilities to create initial weights. In particular, PSU surface area data for selected land cover/uses with small total surface areas (e.g., urban land, farmsteads, streams, and water bodies) were used to improve estimation for these land cover/uses. PSU data were also used to identify temporal patterns in land cover/use at the PSU level that were not found in point data. Estimation procedures were subsequently applied to augment point data so that they reflected these patterns. The role of PSU information in detecting changes too rare to be found in point observations is especially important when developing a data base for efficient estimation of temporal dynamics.

The data collected for MLRAC reporting units are called county base data, and are used as control information in weight calculations. These data represent a census of U.S. surface area, and include surface areas for categories such as transportation (rural roads and railroads), federal land, and Census water (rivers >0.2 km [one-eighth mile] wide and lakes >16.2 ha [40 acres] in size) within each MLRAC for each of the three survey years. These data were used as control totals to develop weights that sum to the correct surface area for each county as defined by the Census Bureau, and to the correct area for each MLRA as determined by USDA. County base data were also used to detect temporal patterns that exist on the land, but had not been observed in point data.

Statistical Methods for Database Construction

Estimation objectives

The 1992 NRI estimation and weight calculation procedures were designed to produce a complete point-level data set with one sample weight for each point, where sample weights were controlled to reflect known surface areas and to provide consistency with historical survey results. This format was selected to provide a data set that would easily support statistical analyses for a wide range of users. The statistical methods developed to accomplish this goal include imputation of missing historical data, imputation of pseudo points to represent county base or PSU dynamics not observed in point data, and construction of weights that reproduce known surface areas and previously published historical results. Estimation and weight calculation procedures used to construct the 1992 NRI database are very complex. In what follows, we briefly describe aspects of these procedures that relate to detecting changes over time. See Nusser and Goebel (1997) for a more comprehensive discussion of these methods.

Imputing missing data

The 1992 sample consisted mainly of PSUs selected for the 1982 NRI, plus a small number of PSUs added in 1987 and 1992 to address sample size concerns. In 1987, only about one-third of the 1982 PSUs were selected for observation due to budget constraints. However, where photography was available, 1987 conditions were recorded during the 1992 data-gathering effort for those PSUs not included in the 1987 sample. Missing data occurred for PSU and point variables on PSUs whose photographic materials had not been observed in 1987 or retrospectively observed in 1992, and for a small set of sample units that were added to the sample in 1992. Thus the first estimation step was to impute data for the missing observations so that the analysis data set would be completely populated. A hierarchical hot-deck imputation procedure was used that randomly selects donors with similar land use and agricultural conditions and that are geographically proximal (Nusser and Goebel 1997). The selection procedure prevented imputation of unlikely patterns such as moving from large urban land in one survey year to cultivated cropland in the next survey year. The imputation procedures generated data with realistic temporal patterns while preserving relationships among variables for a sample unit, so that the behavior of imputed data was similar to that of real data. By creating complete data for each sample unit, analyses of temporal patterns are simplified.

Imputing pseudo point data

The second step of estimation involved imputing ''pseudo'' point data in order to incorporate point-level representations of temporal patterns observed in county base data or PSU area measurements but that were not observed in real point data. For example, the county base data might indicate a reduction in federal land from 1987 to 1992 for a particular MLRAC. However, there may be no sample points located in the MLRAC that show a change from federal ownership in 1987 to nonfederal ownership in 1992. We briefly describe the general procedure for imputing point data that reflect changes observed in PSUs. A similar procedure was used for county base pseudo points. These procedures were developed to support efficient estimation of change when investigating temporal dynamics, and to meet the objective of creating a point-level data set that supports easy use of the data and that accurately reflects changes observed for all reported units.

Suppose that area information from a PSU indicates that a net change in surface area occurred for a land cover/use category, but that none of the PSU's points reflect this pattern of change. We know that a change in surface area for a category of land cover/use exists, but we do not know the specific pattern leading to the change. For example, if the change is an increase in surface area for the land cover/use, the preceding land cover/use is unknown. Similarly, if the change is a decrease in surface area for the land cover/use, the new land cover/use is unknown. Data for the PSU pseudo points were imputed from two sources of real point data. In one step, a cover/use classification was imputed

for the year(s) with unknown land use. The cover/use data and the associated characteristics were imputed by randomly selecting one of the points in the PSU or, if necessary, from a nearby PSU using procedures similar to those used in imputing missing data. The imputation was controlled by defining a set of acceptable donor land cover/uses for each possible pattern in the PSU land use dynamics and a hierarchical set of acceptable locations, with the objective of selecting donors that had characteristics similar to those of points in the recipient PSU. A second donor was used to impute data elements for the years in which the land cover/use is known, and was selected using hierarchical controls described above.

This procedure generated a pseudo point with the observed change in the PSU. A second procedure was used to incorporate observed information on the magnitude of the change in surface area into weight calculations. Initial weights were assigned to pseudo and real points on the basis of the observed PSU areas. For example, the initial weight for the pseudo point showing the observed change in land use for the PSU was set equal to the observed change in surface area in the PSU divided by the inclusion probability for that PSU. A second point was used to represent the base surface area from which the land cover/use area had increased, or to which the area had declined. This point was real or imputed from a nearby PSU. The initial weight for the second point was set equal to the base surface area for the land cover/use divided by the PSU selection probability. This allocation insures that the magnitude of temporal changes in the cover/use for the PSU is accurately reflected in the point data for all survey years.

Weight calculation

In working with finite populations, there frequently exists known information about the population that can be incorporated into sample weight calculations so that weighted estimates constructed from the survey data reproduce the known information, often referred to as ''controls.'' For the 1992 NRI, control information included surface areas for selected political and regional areas, as well as small area estimates of urban land. In addition, controls were incorporated into final weight calculations so that 1982 NRI estimates of surface areas for 14 land cover/use categories would be reproduced when estimates of 1982 surface area for these cover/use classes were computed from the 1992 NRI database. These restrictions were used because the 1982 NRI is believed to be the best source of surface area estimates for these categories during the 1982 growing season, and because they serve to provide consistency across versions of the database as more time points were added. Some exceptions in consistency were permitted, for example, when substantial revision of the data had occurred as a result of revised definitions or protocols. Control information was also incorporated so that weights for points located in Conservation Reserve Program (CRP) land summed to known state totals for surface area enrolled in CRP. Standard survey estimation procedures of raking, ratio estimation, and small area estimation were adapted to implement operationally feasible algorithms for calculating a final weight for each point in the database.

The final product of the estimation and weight calculation process was a database containing 1982, 1987, and 1992 conditions for each point in the database. Each point record included one weight, in units of 0.405 km^2 (100 acres), as well as stratum and cluster variables to support variance estimation.

Analyzing Dynamics of Change

General approach

Large-scale natural resource and ecological surveys frequently have a limited number of time points in the survey series. Traditional time-series methods are not well suited for this situation. An alternative approach is to characterize the change in conditions at a point by a sequence of ''states,'' using a classification variable to describe the states. In NRI analyses, states frequently relate to specific agricultural land uses. Of interest is how a response variable, such as erosion rates or conservation practices, changes in relation to the historical progression of conditions for the sample unit. The sequence of conditions for a sample unit provides information on the mechanisms that might be affecting the response variable. We illustrate this approach with an example from the 1992 NRI in which data on temporal dynamics are used to investigate factors affecting a response variable. Our objective is to examine the relationship between temporal patterns in land use and changes in soil loss resulting from water erosion.

Data

Three factors that influence water erosion are the inherent erodibility of the land, cultivation practices, and participation in the Conservation Reserve Program (CRP). CRP was initiated in 1986 to remove land from crop production and to place it in a land cover that promotes soil and wildlife conservation. According to NRCS definitions, point j in PSU i from stratum h is considered highly erodible at time t if the erodibility index, E_{hijt}, is greater than or equal to eight, where $E_{hijt} = T_{hij}^{-1}(R_{hij}K_{hij}L_{hijt})$, R is the rainfall factor from the Universal Soil Loss Equation (USLE), K is the soil erodibility USLE factor, L is the slope length, and T is the soil loss tolerance factor. Note that the erodibility index will not change over time unless the slope length has been altered, for example, by terracing.

Each point from the 1992 database can be classified as belonging to one of four categories in each year: 1 = cultivated, highly erodible cropland not in CRP, 2 = other cropland not in CRP, 3 = cropland in CRP,

and 4 = non cropland uses. Let Q_{hijt} denote the land use classification for point j in PSU i from stratum h during year t. Because there was no CRP program in 1982, a point cannot be classified as belonging to the third category in 1982. Thus there are (3)(4)(4) = 48 possible temporal sequences for a point, $\mathbf{Q}_{hij} = \{Q_{hij1}, Q_{hij2}, Q_{hij3}\}$, where t = 1, 2, 3 corresponds to 1982, 1987, and 1992 data, respectively.

The soil erosion rate due to water runoff (expressed as soil mass per unit area per year), y_{hijt}, for point j in PSU i in stratum h during year t is calculated using the USLE, defined by $y_{hijt} = R_{hij}K_{hij}L_{hijt}C_{hijt}P_{hijt}$, where C is the cropping management factor, P is the erosion control practice factor, and R, K and L are defined above.

Estimating total surface area and mean erosion rates

We begin by estimating the total surface area associated with each of the 48 possible land cover/use patterns. Let w_{hij} be the final weight for point j in PSU i and stratum h. Let

$$z_{\mathbf{k}hij} = \begin{cases} 1 & \text{if point } hij \text{ exhibits temporal sequence } \mathbf{Q}_{hij} = \mathbf{k} \\ 0 & \text{otherwise} \end{cases}$$

where $\mathbf{k} = (k_1, k_2, k_3)$ and k_t (t = 1, 2, 3) takes on values corresponding to the land use categories defined previously. A survey estimator for the total surface area of land following the temporal sequence indexed by $\mathbf{k}$ is $\hat{A}_{\mathbf{k}} = \Sigma_h \Sigma_i \Sigma_j w_{hij} z_{\mathbf{k}hij}$.

Ratio estimation (Cochran 1977) is used to estimate the mean rate of soil loss due to water erosion. The estimated mean erosion rate (in megagrams per hectare per year) at time t for points in temporal sequence $\mathbf{k}$ is defined by $\hat{\mu}_{\mathbf{k}t} = \hat{A}_{\mathbf{k}}^{-1} \Sigma_h \Sigma_i \Sigma_j w_{hij} z_{\mathbf{k}hij} y_{hijt}$, where y_{hijt} is the calculated erosion rate for point hij at time t defined previously. The change in rate from 1982 to 1992 is thus $\hat{\mu}_{\mathbf{k}3} - \hat{\mu}_{\mathbf{k}1} = \hat{A}_{\mathbf{k}}^{-1} \Sigma_h \Sigma_i \Sigma_j w_{hij} z_{\mathbf{k}hij}(y_{hij3} - y_{hij1})$.

Variance estimation

As previously described, the basic sample for the 1992 NRI is a stratified two-stage sample. Recall that procedures were used to impose restrictions on the weights so that control information was incorporated. If some of these restrictions represent population totals, for example the state CRP surface areas, they reduce the variance of characteristics correlated with the control variable. In NRI, these correlations are negligible for most characteristics, and the usual variance formulas for a stratified two-stage design, such as those implemented in the software PC CARP (Fuller et al. 1986), are adequate approximations. The exceptions are items closely related to CRP. For these items we use the variance of a ratio estimator. See Cochran (1977) for the variance of stratified designs and ratio estimators.

Results

One way to approach analyses of NRI temporal patterns is to consider two years at a time. For example, Table 1 contains estimated total surface area and mean erosion rates describing erosion trends from 1982 to 1992 for temporal sequences defined by (k_1, k_3). Rows of Table 1 represent a 1982 classification for the point (k_1), and columns represent the 1992 classification (k_3). The cells in Table 1 contain estimates of the surface area associated with the pattern of change from 1982 to 1992, the change in erosion rates between the two years for a particular temporal pattern of land use, and the erosion rate for each year individually for the cell's land use patterns. Marginal estimates are also provided. Erosion rates are expected to decline if land is shifted from cultivated cropland to other uses. Thus large decreases in erosion are observed for the three cells of the first row in which this change occurs. There has also been a reduction in erosion in the first cell. This can be due to two sources: the more erodible land may have been moved to other uses, and/or improved practices may have been applied to land remaining in cultivation. In a similar fashion, land that moves into cultivation shows an increase in erosion.

As more than two years are considered, multiple two-dimensional tables are required to present summary statistics, and it becomes difficult to extract relationships. Matrices of plots, such as those presented in Carr and Nusser (1995), can be used to represent temporal patterns in erosion rates for the different classifications. In Fig. 2, erosion rates are plotted over the three time points for the same cells as those found in Table 1. These plots show the erosion rates for the 1987 transition category between 1982 and 1992. Consider the first row of plots, which shows temporal erosion patterns for 1982 highly erodible cultivated cropland. Fig. 2 shows that erosion rates for land classified as highly erodible cultivated cropland in 1982 declined when other land uses were applied in subsequent years. Highly erodible cultivated cropland that was enrolled in CRP in 1987 and returned to other cropland uses exhibited similar 1982 and 1992 erosion rates, indicating that the CRP effect on erosion rates was not retained. On the other hand, 1987 CRP land that was moved into noncropland uses by 1992 maintained lower erosion rates. Results presented in the other two rows, corresponding to points with 1982 other cropland and noncropland uses, are also consistent with that observation.

Table 2 contains information on the estimated surface area associated with each land use pattern for the same cells as defined for Fig. 2. The table indicates the relative importance of land use dynamics in the landscape and thus is useful in interpreting the impact of erosion patterns observed in Fig. 2 on overall soil loss. For example, consider the change in erosion rates for land classified as highly erodible cropland in 1982, CRP in 1987, and not cropland in 1992 (sequence 1,

TABLE 1. National estimates of total surface area (km^2) and mean erosion rates (Mg·ha^{-1}·yr^{-1}) for 1982 and 1992 land use classifications. Standard errors are presented in parentheses.

		1992 classification				
1982 classification	Variable	Cultivated cropland EI ≥ 8	Other cropland (not in CRP)	CRP	Noncropland	Total
Cultivated cropland EI ≥ 8	Area (km^2)	289 523.2	30 674.6	67 818.8	30 936.8	418 953.5
		(2138.4)	(635.4)	(978.9)	(587.6)	(2618.4)
	Erosion rate	18.72	22.69	19.12	27.24	19.70
	(82 USLE)	(0.16)	(0.54)	(0.47)	(0.61)	(0.13)
	Erosion rate	15.00	5.18	1.88	2.22	11.20
	(92 USLE)	(0.13)	(0.15)	(0.09)	(0.11)	(0.09)
	Change	−3.72	−17.50	−17.24	−25.02	−8.50
		(0.09)	(0.49)	(0.45)	(0.61)	(0.11)
Other cropland	Area (km^2)	21 110.3	1 120 602.2	60 942.6	82 017.7	1 284 672.8
		(572.6)	(3218.6)	(950.6)	(951.4)	(3467.9)
	Erosion rate	6.16	5.58	6.90	5.34	5.63
	(82 USLE)	(0.26)	(0.02)	(0.13)	(0.07)	(0.02)
	Erosion rate	16.05	4.73	0.92	0.90	4.48
	(92 USLE)	(0.49)	(0.02)	(0.04)	(0.04)	(0.02)
	Change	9.9	−0.85	−5.96	−4.43	−1.14
		(0.40)	(0.02)	(0.11)	(0.08)	(0.02)
Noncropland	Area (km^2)	25 027.1	60 298.7	8998.5	6 053 259.8	6 147 584.0
		(718.7)	(879.4)	(413.2)	(24 399.8)	(24 402.2)
	Erosion rate	2.17	2.53	2.15	1.30	1.32
	(82 USLE)	(0.11)	(0.60)	(0.15)	(0.02)	(0.02)
	Erosion rate	19.72	3.99	1.36	1.23	1.32
	(92 USLE)	(0.69)	(0.06)	(0.11)	(0.22)	(0.22)
	Change	17.55	1.43	−0.78	−0.09	0.00
		(0.65)	(0.60)	(0.15)	(0.02)	(0.02)
Total	Area (km^2)	335 660.6	1 211 575.4	137 759.9	6 166 214.4	7 851 210.3
		(2302.7)	(3337.6)	···†	(24 390.9)	(24 263.4)
	Erosion rate	16.70	5.87	12.59	1.48	3.00
	(82 USLE)	(0.13)	(0.04)	(0.22)	(0.02)	(0.02)
	Erosion rate	15.42	4.70	1.43	1.23	2.37
	(92 USLE)	(0.11)	(0.02)	(0.04)	(0.02)	(0.02)
	Change	−1.27	−1.16	−1.19	−0.26	−0.63
		(0.08)	(0.04)	(0.22)	(0.02)	(0.02)

Note: Numbers in parentheses represent one standard error. EI = erodibility index.
† Total CRP surface area in 1992 is a known control total and thus has no variance.

3, 4 in the upper right plot in Fig. 2). This plot suggests that land with the highest erosion rates was quickly moved out of production. However, Table 2 indicates that this pattern only exists on a small area of land: 44.8 km^2 (110 700 acres). In fact, the majority of land area remained in the same land use classification for all three survey years.

DISCUSSION

We have provided a brief presentation of statistical methods used to conduct the NRI along with an example of analyses designed to explore the influence of temporal patterns on a response variable. We now discuss these procedures and how they support investigations of the dynamics of change from a more general perspective.

The use of a unified sample design across natural resources and through space and time is a cornerstone to investigating the dynamics of change in an ecological system. By collecting data on multiple dimensions of a natural resource system during a common time period, confounding is reduced and the potential for complex investigations is increased. It is well known that repeated observations on the same sample unit lead to efficient estimation of change over time for variables of the type observed in the NRI (Kasprzyk et al. 1989, Fuller 1990). When data are collected on multiple facets of an ecosystem, repeated observations have the additional advantage of providing time series that support investigations of the dynamics of change. For example, in the NRI, soil erosion is one of the primary monitoring variables. Temporal observations on the type of crop cover, conservation practices applied to the point, and an index for erosion potential based on soil properties make it possible to study the effectiveness of various cropping systems and conservation practices in reducing soil erosion. Alternatively, in a different type of survey, if net increases in chemical use and water contamination are observed over time, historical patterns of chemical usage associated with sample units can be used to relate practices to water contamination trends. This type of information can suggest hypotheses for the underlying causal mechanisms contributing to increased contamination.

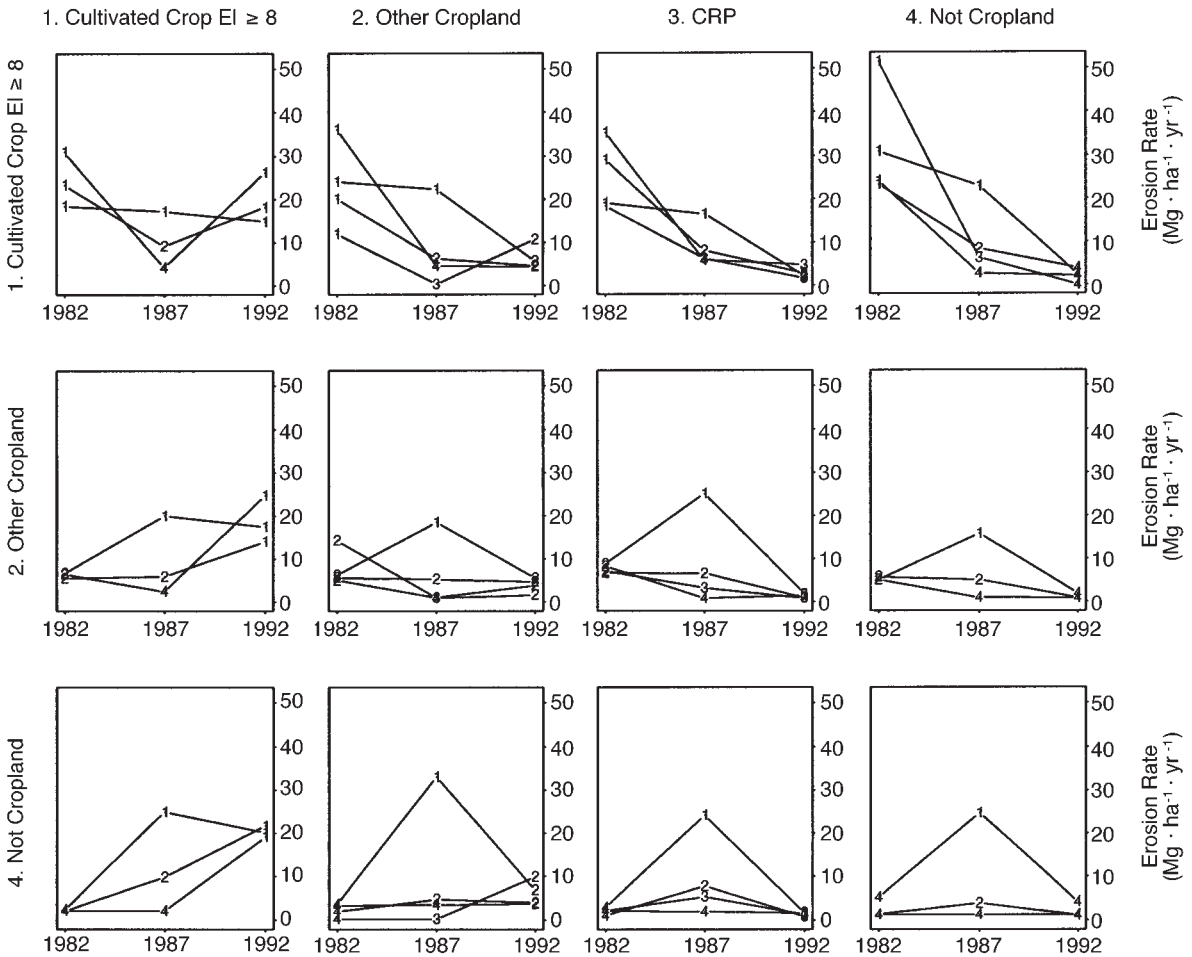

FIG. 2. National water erosion patterns in relation to land use. Water erosion rates are estimated from the 1992 National Resources Inventory. Rows correspond to 1982 land use classification and columns to 1992 land use classification. Plot symbols 1–4 correspond to land use classification in a given year as defined along the plot margins.

An integrated longitudinal survey design applied to the entire population of interest provides flexibility in defining study regions, groupings of land uses or ecological communities, or other classifications to address a broad range of questions. For instance, it is not always possible to predict which areas will experience interesting temporal dynamics or to know which variables will be of interest in studying natural resource dynamics. Unified sample designs can be readily modified for many types of smaller special studies, contributing responsiveness to monitoring programs. For example, in recent years, special NRI samples have been selected from the national NRI sample to examine topics related to wetlands, erosion rates in relation to conservation programs, and the effect of high commodity prices and the 1996 Federal Agricultural Improvement and Reform Act on field intensification and conservation practices. Because the national sample size is relatively large and well distributed in areas of interest for natural resource studies, most special samples can be drawn as a second phase from the national sample. One advantage of using a multiphase sampling approach is that historical data can be used to provide a more detailed analysis of current status and trends. In addition, summary statistics generated from the national sample can be used in weight construction to improve the precision of estimates generated from a much smaller sample size.

Samples for any study should be drawn from the entire target population. This can be difficult in ecological studies because the boundaries of natural populations, such as an area defined by specific land uses, a species population, or an ecological community, frequently shift over time. Often historical data are the only information available on the location of the population. Because of this, it is advantageous to develop sample frames for monitoring studies that extend beyond the target population(s). For example, if wetlands are of interest, sample units not previously classified as wetlands, but that could become wetlands, should be included in the frame. A broader frame definition allows detection of changes in the geographical range

TABLE 2. Estimated surface area estimates (km^2) for each 1982–1987–1992 land use pattern. EI = erodibility index.

		1992 classification			
1982 classification	1987 classification	Cultivated cropland EI ≥ 8	Other cropland (not in CRP)	CRP	Noncropland
Cult. cropland EI ≥ 8	Cult. cropland EI ≥ 8	278 875.5	17 992.6	36 332.3	14 468.4
	Other cropland (not in CRP)	9273.7	12 221.1	1302.7	1086.2
	CRP	0.0	13.0	29 641.4	0.4
	Noncropland	1374.0	448.0	542.3	15 381.8
Other cropland	Cult. cropland EI ≥ 8	11 845.6	6114.6	1289.4	879.4
	Other cropland (not in CRP)	9064.9	1 110 568.8	37 045.4	37 387.4
	CRP	0.0	1.6	22 260.5	0.0
	Noncropland	199.9	3918.3	347.2	43 750.9
Noncropland	Cult. cropland EI ≥ 8	13 147.5	1495.8	1525.7	3055.5
	Other cropland (not in CRP)	954.3	34 448.9	1068.8	4252.6
	CRP	0.0	6.9	3928.8	0.0
	Noncropland	10 925.3	24 347.2	2475.1	6 045 966.3

of a natural resource or an ecosystem, and provides robustness as study objectives change over time. For example, although the NRI has historically been concerned with nonfederal lands, the original sample is of the entire U.S. surface area, including federal lands. Because of this, changes in the boundaries of nonfederal lands have had little impact on sample design and estimation.

The temporal nature of monitoring studies generates numerous statistical challenges when constructing a database for analysis. It is useful to apply procedures that provide a consistent time series as the survey is repeated. In some cases, this may involve restrictions on weights that incorporate estimates of prior conditions produced from previous surveys. This is the motivation for the use of 1982 estimated surface areas in the 1992 NRI. In other cases, known totals from external sources can be incorporated to provide consistency with information published by other agencies and programs. For example, if the universe is an area of land, then procedures can be developed to include known surface areas of political units or other types of geographic polygons in weight calculations, as is the case with county base data in the NRI.

The form of the final database for analysis can also introduce complications. Often a point-level database is the most convenient. However, in producing a point data set from a complex survey such as NRI, patterns of change that are observed for larger reporting units must somehow be included in the point data. The imputed pseudo point procedure was designed to address this problem. This approach was applied in lieu of classical two-phase estimation, in which regression is used to incorporate PSU information into the weight for the secondary sampling unit (point). In the classical problem, it is assumed that the variable of interest is observed in the second-phase sample. In the case of land use patterns, the change within the MLRAC is not observed in the second-phase sample. As a consequence, classical two-phase estimators for small areas are more variable than the pseudo point imputation procedure due to the absence of real points representing known land use changes in the PSU. In particular, the lack of real points following observed patterns in PSU and county base data results in many estimates of zero change for certain land use categories, even though the actual PSU data indicate a change in land use has occurred. When data are aggregated, for example to the state level, the two procedures are equivalent for land cover/use indicators, but the estimates will differ for other characteristics such as erosion rates or wildlife cover. Breidt et al. (1996) have shown that the imputation procedure is generally unbiased and provides more precise estimates of change than standard two-phase estimation for items such as surface area in vegetative cover classes.

Large multiresource monitoring surveys involve data collection for hundreds of variables over time. The resulting databases can be used for many types of investigations, and the possibilities for analyses are virtually unlimited. However, it can be difficult to present multi-dimensional time series information clearly. New graphical approaches are being developed to translate tabular information to plots (Carr 1994). The graphical presentation of NRI erosion results extends this work to show patterns of change in land cover/use and ero-

sion rates for more than two points in time. Further research is needed to develop methods of including standard errors and measures of the relative importance of the land cover/use dynamics (e.g., estimated surface areas) on the erosion rate plots (Carr and Nusser 1995). Although we have considered temporal patterns as characterized by movement among a few discrete states, alternative formulations of time series are also of interest. Display of patterns that are described by a series of continuous values or numerous discrete states will require a modified approach.

The focus of this special issue is to consider statistical methods for a wide range of environmental and ecological monitoring studies, from intensive site investigations to national monitoring programs. While this paper has described survey methods for trend detection in large-scale investigations, many of the statistical approaches are more broadly applicable. Scientific investigations of any scale, particularly those that require comparable information across time, should make use of statistical sample designs, and multiple scales of study can be addressed using a single design approach. For example, when networks of sites are of interest, a unified sampling design can be used to select sites and to provide a natural framework for combining results from network sites. The methods proposed to create accessible databases when data are collected on more than one reporting unit are useful for intensive sites as well as regional and national studies. Similarly, the methods presented for displaying the dynamics of change are suitable for monitoring studies of all scales that have a limited number of observations across time.

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