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Introduction

1.1 A View on Survey and Monitoring

Survey and monitoring of natural resources are becoming increasingly important worldwide. Although we have no reliable figures, it is safe to say that survey and monitoring activities have grown rapidly during the past 50 years, both in number and diversity, and continue to do so. Two reasons for this are apparent: human pressures on natural resources are increasing dramatically, and public awareness of their vulnerability and the necessity of sustainable use has risen sharply. Exhaustion of non-renewable resources (e.g., fossil fuels), and deterioration due to pollution, erosion, desertification and loss of biodiversity are now widely recognized as threats to human life. The rational management, protection, and use of natural resources at various decision levels all need reliable information on these resources, and this information can only be gathered by observation.

Definitions

Survey means collecting information on an object with a spatial extent through observation, such that possible changes of the object during the observation are negligible. The result of a spatial survey may consist of one or more statistics of the object as a whole, so-called ‘global quantities’, or it may relate to the spatial distribution of properties within the object: so-called ‘local quantities’. Examples of a survey aimed at global quantities are: (a) establishing the mean clay content of the topsoil of an arable field, and (b) establishing the areal fraction of a region occupied by a given vegetation type. Examples of a survey aimed at local quantities are: (a) establishing the mean clay content of the topsoil of sections of an arable field, and (b) mapping the vegetation types in a region. Broadly speaking, the reason for survey is to provide a factual basis for management (e.g., in the context of precision agriculture or countryside stewardship), or for scientific research.

Survey of the same object may or may not be repeated in time. If it is repeated, and the reason for this lies in the need to keep track of possible changes in the object, i.e., to *update* the existing information, this represents an instance of ‘monitoring’.

According to Webster’s dictionary, monitoring is: “to watch, observe or check for special purposes”. The good part of this definition is that it links monitoring explicitly with ”special purposes”, to the extent that without a special purpose we should not even speak of monitoring. Nevertheless, for the purpose of this book, two essential elements are missing in this definition. First, monitoring is repeated and continued for a shorter or longer period of time. Second, observation is being done in a more-or-less systematic way. Generally speaking, monitoring of natural resources should provide the information that is necessary for taking proper decisions on natural resources management.

Hence our definition: monitoring is *collecting information on an object through repeated or continuous observation in order to determine possible changes in the object.* Note that the object of monitoring may or may not have a spatial extent. If it has, observation can proceed via sampling in space–time. An example of an object without spatial extent is a point in a river where water levels are measured repeatedly: a case of sampling in time.

Not every sequence of surveys of the same object is regarded as monitoring. For instance, the soil in a region may be surveyed at successively larger cartographic scales (changing spatial resolution), starting with a ‘reconnaissance’ and then mapping at semi-detailed and detailed scales. In this case, the reason for returning to the same object is not to update the information (as the properties concerned are virtually constant in time), but rather the need to *upgrade* the existing information. Apart from greater precision, the aim of upgrading may also be to provide information on new properties. In practice, combinations of updating and upgrading also occur. All in all, we distinguish five situations with respect to observation:

1. Single observation on an object with spatial extent: ‘survey’;
2. Sequence of surveys for upgrading: collectively called ‘survey’;
3. Sequence of surveys for updating: collectively called ‘monitoring’;
4. Sequence of surveys for updating and upgrading: collectively called ‘monitoring’;
5. Repeated observation on an object without spatial extent: ‘monitoring’.

In this section, we have made a distinction between survey and monitoring, which necessarily stressed the difference between them. We made the distinction because it has important implications for the design of schemes and the choice of methods. On the other hand, the reason why we treat these two kinds of activity in one book lies not in their differences, but in their similarities. The main similarity is that survey and monitoring are both based on sampling: sampling in space for spatial survey and sampling in time or space–time for monitoring. Many sampling-related methods and techniques are generally applicable: in space, in time and in space–time. Therefore it is economical to cover both survey and monitoring in the same book. From the user's point of view, this is appropriate as well, because a common approach to monitoring is to perform it as a more or less coordinated sequence of surveys.

Objects and Techniques

The object of survey or monitoring can be any natural or semi-natural system. Examples include a river, a forest, the soil of a farm, the groundwater in a region, the vegetation in a conservation area, the rainfall on a continent, the atmosphere of the world. These examples illustrate the wide variety of possible objects, in terms of both their nature and their spatial extent. The temporal extent of monitoring also varies greatly: from a few months, e.g., a growing season of a crop, to more than a century in the case of meteorological monitoring.

With regard to soil, a traditional type of monitoring is for the nutrient status of agricultural fields as a whole, while recently schemes are being developed to monitor variations within fields, to support precision agriculture. Also, in the last decades schemes have been set up to monitor soil quality and soil pollution at a regional or national scale.

Monitoring in hydrology shows a large variety of aims and scales. As for soil, monitoring of open water as well as groundwater may be directed to quality and pollution, or otherwise to quantity, with water level as an important aspect. Monitoring in ecology has still a wider scope than in soil science and hydrology; important objectives are evaluation of effects of environmental changes on species abundances and occurrence of vegetation types.

A huge variety of observation techniques are used for survey and monitoring, ranging from remote sensing to proximal sensing techniques, from simple field observations to highly advanced laboratory analyses, from a single observation to hundreds of different observations made per sampling unit. The observations can be made on a nominal, ordinal, interval or ratio scale. Observations can be made directly on the object, or indirectly, by pre-processing the results of one or more direct observations.

Aims

With a view on designing monitoring schemes, it is useful to distinguish three categories of monitoring according to its aim (Dixon and Chiswell, 1996; Loaiciga et al., 1992):

- *status monitoring* for quantitative description of the universe as it changes with time;
- *trend monitoring* to decide whether temporal trends are present in the universe;
- *regulatory* or *compliance monitoring* to decide whether the universe satisfies regulatory conditions.

In *status* or *ambient* monitoring, the aim is to characterize the status of the object, and to follow this over time. Examples are: the timber volume of a forest, the presence of indicator plant species in an ecosystem, the leaching of nitrate to the groundwater from the soil of a farm, the emission of greenhouse gases by a country, the climate in a given part of the world. The main reasons for this type of monitoring are that information about the system is needed for management, administration, regulation or scientific research.

In *trend* or *effect* monitoring, the aim is to study the possible effects of a natural event or a human activity on the object, for instance the effect of drinking water extraction by a pumping station on the water tables in a region, the effect of a hydrologic measure against desiccation of an ecosystem in a conservation area, the effect of a change in agricultural policy on the land use in a country. Thus, the aim of effect monitoring is not only to find out whether there has been a change, as in status monitoring, but also to establish whether the change was caused by a specified event or measure. The reasons for effect monitoring are similar to those for status monitoring.

In *compliance* or *regulatory* monitoring, the aim is to decide whether the object complies with a given regulatory standard, e.g., to check whether a system of obligatory crop rotation is actually being applied in an agricultural region, or whether heavy metal concentrations in soil used for crop production remain below specified maximum levels. The reason for compliance monitoring is generally law enforcement.

The above broad distinction of aims is relevant to sampling, because for status monitoring the sampling should allow efficient estimation or prediction of descriptive parameters repeatedly, while for trend and regulatory monitoring it should provide statistical validity and sufficient power of hypothesis testing or acceptable error rates in classifying the object into categories. (See Sect. 2.2 for these modes of statistical inference.)

1.2 Aim and Scope

The aim of this book is to present to practitioners the statistical knowledge and methodology needed for survey and monitoring of natural resources. We intend to omit all theory not essential for applications or for basic understanding. Where possible, we refer to the sampling and monitoring literature for specific topics. In one respect, however, this presentation is broader than standard statistical texts: we pay much attention to how statistical methodology can be employed and embedded in real-life survey and monitoring projects. Thus, we discuss in detail how efficient schemes for survey and monitoring can be designed in view of the aims and constraints of a project.

Our scope is limited to *statistical methods*, because these methods allow the quality of results to be quantified, which is a prerequisite for optimization of survey or monitoring schemes, as well as for risk management and quality control. A further limitation is imposed by the assumption that complete observation of the object is not feasible, so that the survey or the monitoring must be conducted by observations on one or more *samples* from the object. Since budgets for survey and monitoring are and will remain limited, it is important to know how to design cost-effective schemes.

The book presents statistical methods of *sampling* and *inference* from sample data. From a statistical point of view, the core of survey and monitoring is first of all *sampling*, either in space (at a single instant but at multiple locations), or in time (at a single location but at several instants), or in space–time (at multiple locations and times). Sampling is therefore the main focus of this book. However, not all sampling in space and/or time is directly aimed at survey or monitoring purposes. For instance, in scientific research, the purpose of sampling may be to generate a hypothesis about a physical or ecological process, to calibrate a model, or to describe relationships via multivariate analysis. Sampling for such purposes is not covered by this book. Obvious exceptions are sampling for variogram modelling (Chap. 9) and time-series modelling (Chap. 13), because such models are essential for model-based survey and monitoring. A borderline case is where a sample is taken to build a regression model, which is then used to make predictions about the target variable at grid nodes in space, as a method of survey. In this case, the sample is used only indirectly for survey and, from a statistical point of view, sampling for regression modelling is quite different from sampling directly for survey or monitoring. This is why we do not address this case.

We present methodologies that we consider to be generally useful for survey and monitoring of natural resources. We do not, however, cover highly specialized methods of geologic, meteorologic and faunistic survey and monitoring, nor do we treat sampling of lots of natural products or sampling for detection of local critical conditions (Sect. 2.2.6).

The spatial scale varies from a single agricultural field, as in precision agriculture, to continental, as in monitoring the water quality of large rivers. The temporal extent in monitoring varies from, say, a growing season, to many decades in long-term monitoring of variables such as water tables.

Although the methodology presented in this book is widely applicable in natural resource monitoring, the examples that we present to illustrate these methods are mostly taken from our own background knowledge: soil, groundwater, land use, landscape and, to a lesser extent, vegetation.

1.3 Basic Concepts and Terminology

The natural resources about which survey or monitoring in a given application intends to provide information are referred to as the *universe of interest*, or briefly the *universe*. Universes in this context are biotic or a-biotic systems varying in space and/or time. Some universes may, for the purpose of sampling, be regarded as a physical continuum, e.g., the soil in a region at some moment, the water of a river passing a point during a period, the crop on a field at some time[1], or the natural vegetation in an area during a period[2]. The number of dimensions of continuous universes may be 1, 2 or 3 for spatial universes, 1 for temporal universes, and 2, 3 or 4 for spatio-temporal universes. Discrete universes are populations of individual entities, such as the trees in a forest, the lakes in a province, the arable fields in a region, or the growing seasons of a crop in a region. Although the individuals of a discrete population have dimensions and positions in space and time, contrary to continuous universes, a discrete universe itself has no measure of size other then the number of individuals in it.

We use the term *sampling* in the usual broad sense of selecting parts from a universe with the purpose of taking observations on them. The selected parts may be observed in situ, or material may be taken out from them for measurement in a laboratory. The collection [3] of selected parts is referred to as the *sample*. To avoid confusion, a single part that is or could be selected is called a *sampling unit*. The number of sampling units in a sample is referred to as the *sample size*. The material possibly taken from a sampling unit is referred to as an *aliquot*. Aliquots from different sampling units bulked together form a *composite aliquot* or briefly a *composite*.

The individuals of discrete universes naturally act as sampling units. Sampling units from a continuous universe have to be defined more or less arbitrarily. However defined, any sampling unit has a shape and a size. Within the universe it has an orientation (if the shape is not round) and a position. Shape, size and orientation together are referred to as the *sample support*. The dimensions of a sampling unit may be so small compared with the universe, that they can be neglected. In that case the unit can be identified by a point in space and/or time, and we speak of *point support*. In ecological monitoring the sampling units are usually two-dimensional in space, and referred to as *quadrats*.

We refer to the position of a sampling unit in space-time as a *sampling event*, with a *sampling location* and a *sampling time*. Of course, when sampling from a spatial universe, the sampling time is irrelevant from a statistical point of view, and we shall speak about the sampling locations only. Similarly, when sampling from a temporal universe, the sampling location is irrelevant, and we shall speak about the sampling times only. However, a sampling event in a spatio-temporal universe must identified by both location and time. For instance, an observation taken at such an event could be the water-table elevation at a given location and a given time. The same location and a different sampling time would make a different sampling event, as would a different

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[1] A ‘continuum view’ of crop is appropriate if the interest lies in crop properties per areal unit of the field. However, if the interest lies in properties per plant, then the universe is to be regarded as a discrete population.

[2] A monitoring period may or may not have a pre-defined end.

[3] If each part occurs only once in the collection, as is usually the case, then it is a set. In probability sampling, however, there are two forms of collection: *sets* in sampling without replacement, and *sequences* in sampling with replacement

location and the same sampling time. Also, when dealing with positions of sampling units in a universe in general, without specifying whether this is spatial, temporal or spatio-temporal, we shall use the generic term ‘sampling event’.

The positions of all sampling units of a sample together form a pattern in space and/or time, referred to as a *sampling pattern*. Selecting a sample can thus be done by selecting a sampling pattern. Very often, the actual selection of sampling units is not done in the field but in the office, using some representation of the universe, such as a list or a map. This representation is called a *sampling frame*.

More terms are explained elsewhere in this book, where they are first introduced. A subject index is provided at the end.

1.4 Structure and Use of this Book

We tried to structure this book such that a scientist who has to set up a survey or monitoring project, can find ample guidance in how to analyze his/her particular monitoring or survey problem, and how to select the methods to solve it. Part I is entirely devoted to this. Those who are looking for methods which optimally fit their specific purpose, especially beginners in this field, are advised to read this part before going to the methodological parts.

Part I is composed of four chapters. The preparatory Chap. 2 recapitulates the various modes of sampling unit selection and of statistical inference from sample data. Chapter 3 presents seven principles that we consider essential for scheme design. Chapter 4 discusses three major design decisions: (1) the choice between design-based and model-based inference, (2) the choice of sample support, and (3) choices on composite sampling. Finally, Chap. 5 deals with optimization of sample selection.

After the part on scheme design follows the presentation of sampling methods in Parts II, III and IV. We have structured this presentation broadly in a problem-oriented rather than a method-oriented way, to make it as easy as possible to find a suitable method, given the survey or monitoring problem at hand. Therefore, we adopted the following hierarchy to structure the material:

1. at part level, a division according to the dimensions of universe: *space*, *time* or *space–time*;
2. at chapter level, a division according to the kind of target quantity: *global* or *local*;
3. at section level, a division according to the approach to sampling: *design-based* or *model-based.*

Although the latter distinction is method-oriented, it is strongly related to the kind of results that are requested from survey or monitoring. The division into design-based and model-based methods at this high level is also warranted because the choice between them has major consequences, both for the sampling and the inference stages.

Many methods dealt with in this book can be applied to spatial, as well as temporal or spatio-temporal universes. Rather then re-iterating such methods in all three parts, we treat them only in Part II on sampling in space. This part therefore includes many generally applicable methods, thus forming a large portion of the book. For example, Chap. 9 about methods for variograms is placed in Part II, but these methods are equally relevant to survey and monitoring. Similarly, time-series models are only presented in Part III on sampling in time, but they are equally relevant to space–time monitoring.

The price for the above mentioned conciseness is, of course, that one may have to go back to one or even two earlier parts. Thus the reference to parts is as follows:

- sampling for survey: go to Part II on sampling in space;
- sampling for monitoring on a single location: go to Part III on sampling in time, and go back to Part II when needed;
- sampling for monitoring in space and time: go to Part IV on sampling in space–time, and go back to Part II and/or Part III when needed.

Referencing at a more detailed level is provided in the introductory chapter at the beginning of each part.

1.5 Notation

The typographic conventions in this book are as follows.

- Variables: small or capital italic. Target variables, transformed target variables, and ancillary variables are generically denoted with the small letters z, y and x, respectively, if they are deterministic. If they are stochastic, then they are denoted with the capitals Z, Y and X.
- Errors or residuals: e if they are deterministic, and ϵ if they are stochastic.
- Vectors: bold upright small letters $(\mathbf{s}, \boldsymbol{\lambda})$
- Matrices: bold upright capitals $(\mathbf{S},\ \mathbf{C})$
- Transposed vectors and matrices are denoted with a prime $(\mathbf{s}', \boldsymbol{\lambda}')$
- Sets: calligraphic capitals $(\mathcal{S}, \mathcal{U})$, but the usual $\mathbb{R}$ for the set of real numbers
- Size of sets: $|\mathcal{U}|$, etc.

The following general symbolism is used throughout this book.

- Means over spatial, temporal and space–time universes are indicated by bars, for instance: $\bar{z}_{\mathcal{U}}$ is the mean of deterministic variable z in universe $\mathcal{U}$.
- Estimators defined on the basis of sample data are indicated by a hat, for instance: $\hat{\bar{z}}_{\mathcal{U}}$ is an estimator of the mean of deterministic variable z in universe $\mathcal{U}$.

- Predictors defined on the basis of sample data are indicated by a tilde, for instance: $\widetilde{\overline{Z}}_{\mathcal{U}}$ is a predictor of the mean of stochastic variable Z in universe $\mathcal{U}$.
- Prior estimates or 'guesses' are indicated by a breve, for instance: $\breve{\bar{z}}_{\mathcal{U}}$ is a prior estimate of the mean of deterministic variable z in universe $\mathcal{U}$.
- Variances are either denoted with $V(\cdot)$ or $S^2(\cdot)$ or σ^2, depending on the kind of variance. Variances between realizations of a stochastic process are denoted with $V(\cdot)$. Such a process may be repeated sampling (as in the design-based approach), or it may be hypothesized through a stochastic model of spatial or temporal variation (as in the model-based approach). For instance: $V(Z(\mathbf{s}))$ is the variance of stochastic variable Z at location $\mathbf{s}$, as determined by a stochastic model.

  Variances as a measure of dispersion in space, time or space–time are denoted with $S^2(\cdot)$. For instance, $S^2(z_{\mathcal{D}})$ is the variance between all values of variable z within domain $\mathcal{D}$. Variance as a parameter in stochastic models of the variation in space and/or time is denoted with σ^2, also used as short-hand for prediction-error variance in kriging and Kalman filtering.