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A History of Ideas in Survey Sampling Theory

1.1 Introduction

Looking back, the debates that animated a scientific discipline often appear futile. However, the history of sampling theory is particularly instructive. It is one of the specializations of statistics which itself has a somewhat special position, since it is used in almost all scientific disciplines. Statistics is inseparable from its fields of application since it determines how data should be processed. Statistics is the cornerstone of quantitative scientific methods. It is not possible to determine the relevance of the applications of a statistical technique without referring to the scientific methods of the disciplines in which it is applied.

Scientific truth is often presented as the consensus of a scientific community at a specific point in time. The history of a scientific discipline is the story of these consensuses and especially of their changes. Since the work of Thomas Samuel Kuhn (1970), we have considered that science develops around paradigms that are, according to Kuhn (1970, p. 10), "models from which spring particular coherent traditions of scientific research." These models have two characteristics: "Their achievement was sufficiently unprecedented to attract an enduring group of adherents away from competing modes of scientific activity. Simultaneously, it was sufficiently open-ended to leave all sorts of problems for the redefined group of practitioners to resolve." (Kuhn, 1970, p. 10).

Many authors have proposed a chronology of discoveries in survey theory that reflect the major controversies that have marked its development (see among others Hansen & Madow, 1974; Hansen et al., 1983; Owen & Cochran, 1976; Sheynin, 1986; Stigler, 1986). Bellhouse (1988a) interprets this timeline as a story of the great ideas that contributed to the development of survey sampling theory. Statistics is a peculiar science. With mathematics for tools, it allows the methodology of the other disciplines to be finalized. Because of the close correlation between a method and the multiplicity of its fields of action, statistics is based on a multitude of different ideas from the various disciplines in which it is applied.

The theory of survey sampling plays a preponderant role in the development of statistics. However, the use of sampling techniques has been accepted only very recently. Among the controversies that have animated this theory, we find some of the classical debates of mathematical statistics, such as the role of modeling and a discussion of estimation techniques. Sampling theory was torn between the major currents of statistics and gave rise to multiple approaches: design-based, model-based, model-assisted, predictive, and Bayesian.

Sampling and Estimation from Finite Populations, First Edition. Yves Tillé.

1.2 Enumerative Statistics During the 19th Century

In the Middle Ages, several attempts to extrapolate partial data to an entire population can be found in Droesbeke et al. (1987). In 1783, in France, Pierre Simon de Laplace (see 1847) presented to the Academy of Sciences a method to determine the number of inhabitants from birth registers using a sample of regions. He proposed to calculate, from this sample of regions, the ratio of the number of inhabitants to the number of births and then to multiply it by the total number of births, which could be obtained with precision for the whole population. Laplace even suggested estimating "the error to be feared" by referring to the central limit theorem. In addition, he recommended the use of a ratio estimator using the total number of births as auxiliary information. Survey methodology as well as probabilistic tools were known before the 19th century. However, never during this period was there a consensus about their validity.

The development of statistics (etymologically, from German: analysis of data about the state) is inseparable from the emergence of modern states in the 19th century. One of the most outstanding personalities in the official statistics of the 19th century is the Belgian Adolphe Quételet (1796–1874). He knew of Laplace's method and maintained a correspondence with him. According to Stigler (1986, pp. 164–165), Quételet was initially attracted to the idea of using partial data. He even tried to apply Laplace's method to estimate the population of the Netherlands in 1824 (which Belgium was a part of until 1830). However, it seems that he then rallied to a note from Keverberg (1827) which severely criticized the use of partial data in the name of precision and accuracy:

> In my opinion, there is only one way to arrive at an exact knowledge of the population and the elements of which it is composed: it is that of an actual and detailed enumeration; that is to say, the formation of nominative states of all the inhabitants, with indication of their age and occupation. Only by this mode of operation can reliable documents be obtained on the actual number of inhabitants of a country, and at the same time on the statistics of the ages of which the population is composed, and the branches of industry in which it finds the means of comfort and prosperity.[1]

In one of his letters to the Duke of Saxe-Coburg Gotha, Quételet (1846, p. 293) also advocates for an exhaustive statement:

> La Place had proposed to substitute for the census of a large country, such as France, some special censuses in selected departments where this kind of operation might have more chances of success, and then to carefully determine the ratio of the population either at birth or at death. By means of these ratios of the births and deaths of all the other departments, figures which can be ascertained with sufficient accuracy, it is then easy to determine the population of

1 Translated from French: "À mon avis, il n'existe qu'un seul moyen de parvenir à une connaissance exacte de la population et des élémens dont elle se compose : c'est celle d'un dénombrement effectif et détaillé ; c'est-à-dire, de la formation d'états nominatifs de tous les habitans, avec indication de leur âge et de leur profession. Ce n'est que par ce mode d'opérer, qu'on peut obtenir des documens dignes de confiance sur le nombre réel d'habitans d'un pays, et en même temps sur la statistique des âges dont la population se compose, et des branches d'industrie dans lesquelles elle trouve des moyens d'aisance et de prospérité."

> the whole kingdom. This way of operating is very expeditious, but it supposes an invariable ratio passing from one department to another. [· · ·] This indirect method must be avoided as much as possible, although it may be useful in some cases, where the administration would have to proceed quickly; it can also be used with advantage as a means of control.[2]

It is interesting to examine the argument used by Quételet (1846, p. 293) to justify his position.

> To not obtain the faculty of verifying the documents that are collected is to fail in one of the principal rules of science. Statistics is valuable only by its accuracy; without this essential quality, it becomes null, dangerous even, since it leads to error.[3]

Again, accuracy is considered a basic principle of statistical science. Despite the existence of probabilistic tools and despite various applications of sampling techniques, the use of partial data was perceived as a dubious and unscientific method. Quételet had a great influence on the development of official statistics. He participated in the creation of a section for statistics within the British Association of the Advancement of Sciences in 1833 with Thomas Malthus and Charles Babbage (see Horvàth, 1974). One of its objectives was to harmonize the production of official statistics. He organized the International Congress of Statistics in Brussels in 1853. Quételet was well acquainted with the administrative systems of France, the United Kingdom, the Netherlands, and Belgium. He has probably contributed to the idea that the use of partial data is unscientific.

Some personalities, such as Malthus and Babbage in Great Britain, and Quételet in Belgium, contributed greatly to the development of statistical methodology. On the other hand, the establishment of a statistical apparatus was a necessity in the construction of modern states, and it is probably not a coincidence that these personalities come from the two countries most rapidly affected by the industrial revolution. At that time, the statistician's objective was mainly to make enumerations. The main concern was to inventory the resources of nations. In this context, the use of sampling was unanimously rejected as an inexact and fundamentally unscientific procedure. Throughout the 19th century, the discussions of statisticians focused on how to obtain reliable data and on the presentation, interpretation, and possibly modeling (adjustment) of these data.

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2 Translated from French: "La Place avait proposé de substituer au recensement d'un grand pays, tel que la France, quelques recensements particuliers dans des départements choisis, où ce genre d'opération pouvait avoir plus de chances de succès, puis d'y déterminer avec soin le rapport de la population soit aux naissances soit aux décès. Au moyen de ces rapports des naissances et des décès de tous les autres départements, chiffres qu'on peut constater avec assez d'exactitude, il devient facile ensuite de déterminer la population de tout le royaume. Cette manière d'opérer est très expéditive, mais elle suppose un rapport invariable en passant d'un département à un autre. [· · ·] Cette méthode indirecte doit être évitée autant que possible, bien qu'elle puisse être utile dans certains cas, où l'administration aurait à procéder avec rapidité ; on peut aussi l'employer avec avantage comme moyen de contrôle."

3 Translated from French: "Ne pas se procurer la faculté de vérifier les documents que l'on réunit, c'est manquer à l'une des principales règles de la science. La statistique n'a de valeur que par son exactitude ; sans cette qualité essentielle, elle devient nulle, dangereuse même puisqu'elle conduit à l'erreur."

1.3 Controversy on the use of Partial Data

In 1895, the Norwegian Anders Nicolai Kiær, Director of the Central Statistical Office of Norway, presented to the Congress of the International Statistical Institute of Statistics (ISI) in Bern a work entitled *Observations et expériences concernant des dénombrements représentatifs* (*Observations and experiments on representative enumeration*) for a survey conducted in Norway. Kiær (1896) first selected a sample of cities and municipalities. Then, in each of these municipalities, he selected only some individuals using the first letter of their surnames. He applied a two-stage design, but the choice of the units was not random. Kiær argues for the use of partial data if it is produced using a "representative method". According to this method, the sample must be a representation with a reduced size of the population. Kiær's concept of representativeness is linked to the quota method. His speech was followed by a heated debate, and the proceedings of the Congress of the ISI reflect a long dispute. Let us take a closer look at the arguments from two opponents of Kiær's method (see ISI General Assembly Minutes, 1896).

> Georg von Mayr (Prussia)[· · ·] It is especially dangerous to call for this system of representative investigations within an assembly of statisticians. It is understandable that for legislative or administrative purposes such limited enumeration may be useful – but then it must be remembered that it can never replace complete statistical observation. It is all the more necessary to support this point, that there is among us in these days a current among mathematicians who, in many directions, would rather calculate than observe. But we must remain firm and say: no calculation where observation can be done.[4]

> Guillaume Milliet (Switzerland). I believe that it is not right to give a congressional voice to the representative method(which can only be an expedient) an importance that serious statistics will never recognize. No doubt, statistics made with this method, or, as I might call it, statistics, *pars pro toto*, has given us here and there interesting information; but its principle is so much in contradiction with the demands of the statistical method that as statisticians, we should not grant to imperfect things the same right of bourgeoisie, so to speak, that we accord to the ideal that scientifically we propose to reach.[5]

4 Translated from French: "C'est surtout dangereux de se déclarer pour ce système des investigations représentatives au sein d'une assemblée de statisticiens. On comprend que pour des buts législatifs ou administratifs un tel dénombrement restreint peut être utile – mais alors il ne faut pas oublier qu'il ne peut jamais remplacer l'observation statistique complète. Il est d'autant plus nécessaire d'appuyer là-dessus, qu'il y a parmi nous dans ces jours un courant au sein des mathématiciens qui, dans de nombreuses directions, voudraient plutôt calculer qu'observer. Mais il faut rester ferme et dire : pas de calcul là où l'observation peut être faite."

5 Translated from French: "Je crois qu'il n'est pas juste de donner par un vœu du congrès à la méthode représentative (qui enfin ne peut être qu'un expédient) une importance que la statistique sérieuse ne reconnaîtra jamais. Sans doute, la statistique faite avec cette méthode ou, comme je pourrais l'appeler, la statistique, *pars pro toto*, nous a donné ça et là des renseignements intéressants ; mais son principe est tellement en contradiction avec les exigences que doit avoir la méthode statistique, que, comme statisticiens, nous ne devons pas accorder aux choses imparfaites le même droit de bourgeoisie, pour ainsi dire, que nous accordons à l'idéal que scientifiquement nous nous proposons d'atteindre."

The content of these reactions can again be summarized as follows: since statistics is by definition exhaustive, renouncing complete enumeration denies the very mission of statistical science. The discussion does not concern the method proposed by Kiaer, but is on the definition of statistical science. However, Kiaer did not let go, and continued to defend the representative method in 1897 at the congress of the ISI at St. Petersburg (see Kiær, 1899), in 1901 in Budapest, and in 1903 in Berlin (see Kiær, 1903, 1905). After this date, the issue is no longer mentioned at the ISI Congress. However, Kiær obtained the support of Arthur Bowley (1869–1957), who then played a decisive role in the development of sampling theory. Bowley (1906) presented an empirical verification of the application of the central limit theorem to sampling. He was the true promoter of random sampling techniques, developed stratified designs with proportional allocations, and used the law of total variance. It will be necessary to wait for the end of the First World War and the emergence of a new generation of statisticians for the problem to be rediscussed within the ISI. On this subject, we cannot help but quote Max Plank's reflection on the appearance of new scientific truths: "a new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it" (quoted by Kuhn, 1970, p. 151).

In 1924, a commission (composed of Arthur Bowley, Corrado Gini, Adolphe Jensen, Lucien March, Verrijn Stuart, and Frantz Zizek) was created to evaluate the relevance of using the representative method. The results of this commission, entitled "Report on the representative method of statistics", were presented at the 1925 ISI Congress in Rome. The commission accepted the principle of survey sampling as long as the methodology is respected. Thirty years after Kiær's communication, the idea of sampling was officially accepted. The commission laid the foundation for future research. Two methods are clearly distinguished: "random selection" and "purposive selection". These two methods correspond to two fundamentally different scientific approaches. On the one hand, the validation of random methods is based on the calculation of probabilities that allows confidence intervals to be build for certain parameters. On the other hand, the validation of the purposive selection method can only be obtained through experimentation by comparing the obtained estimations to census results. Therefore, random methods are validated by a strictly mathematical argument while purposive methods are validated by an experimental approach.

1.4 Development of a Survey Sampling Theory

The report of the commission presented to the ISI Congress in 1925 marked the official recognition of the use of survey sampling. Most of the basic problems had already been posed, such as the use of random samples and the calculation of the variance of the estimators for simple and stratified designs. The acceptance of the use of partial data, and especially the recommendation to use random designs, led to a rapid mathematization of this theory. At that time, the calculation of probabilities was already known. In addition, statisticians had already developed a theory for experimental statistics. Everything was in place for the rapid progress of a fertile field of research: the construction of a statistical theory of survey sampling.

Jerzy Neyman (1894–1981) developed a large part of the foundations of the probabilistic theory of sampling for simple, stratified, and cluster designs. He also determined the optimal allocation of a stratified design. The optimal allocation method challenges the basic idea of the quota method, which is the “representativeness”. Indeed, depending on the optimal stratification, the sample should not be a miniature of the population as some strata must be overrepresented. The article published by Neyman (1934) in the *Journal of the Royal Statistical Society* is currently considered one of the founding texts of sampling theory. Neyman identified the main fields of research and his work was to have a very important impact in later years. We now know that Tschuprow (1923) had already obtained some of the results that were attributed to Neyman, but the latter seems to have found them independently of Tschuprow. It is not surprising that such a discovery was made simultaneously in several places. From the moment that the use of random samples was considered a valid method, the theory would arise directly from the application of the theory of probability.

1.5 The US Elections of 1936

During the same period, the implementation of the quota method contributed much more to the development of the use of survey sampling methods than theoretical studies. The 1936 US election marked an important turning point in the handling of questionnaire surveys. The facts can be summarized as follows. The major American newspapers used to publish, before the elections, the results of empirical surveys produced from large samples (two million people polled for the *Literary Digest*) but without any method to select individuals. While most polls predicted Landon’s victory, Roosevelt was elected. Surveys conducted by Crossley, Roper, and Gallup on smaller samples but using the quota method gave a correct prediction. This event helped to confirm the validity of the data provided by opinion polls.

This event, which favored the increase in the practice of sample surveys, was made without reference to the probabilistic theory that had already been developed. The method of Crossley, Roper, and Gallup is indeed not probabilistic but empirical, therefore validation of the adequacy of the method is experimental and absolutely not mathematical.

1.6 The Statistical Theory of Survey Sampling

The establishment of a new scientific consensus in 1925 and the identification of major lines of research in the following years led to a very rapid development of survey theory. During the Second World War, research continued in the United States. Important contributions are due to Deming & Stephan (1940), Stephan (1942, 1945, 1948) and Deming (1948, 1950, 1960), especially on the question of adjusting statistical tables to census data. Cornfield (1944) proposed using indicator variables for the presence of units in the sample. Cochran (1939, 1942, 1946, 1961) and Hansen & Hurwitz (1943, 1949) showed the interest of unequal probability sampling with replacement. Madow (1949) proposed unequal probability systematic sampling (see also Hansen et al., 1953a,b). This is quickly established that an unequal probability sampling with fixed size without replacement is a complex problem. Narain (1951), Horvitz & Thompson (1952), Sen (1953), and Yates & Grundy (1953) presented several methods with unequal probabilities in two articles that are certainly among the most cited in this field. Devoted to the examination of several designs with unequal probabilities, these texts are mentioned for the general estimator (expansion estimator) of the total, which is also proposed and discussed. The expansion estimator is, in fact, an unbiased general estimator applicable to any sampling design without replacement. However, the proposed estimator of variance has a default. Yates & Grundy (1979) showed that the variance estimator proposed by Horvitz and Thompson can be negative. They proposed a valid variant when the sample is of fixed sample size and gives sufficient conditions for it to be positive. As early as the 1950s, the problem of sampling with unequal probabilities attracted considerable interest, which was reflected in the publication of more than 200 articles. Before turning to rank statistics, Hájek (1981) discussed the problem in detail. A book of synthesis by Brewer & Hanif (1983) was devoted entirely to this subject, which seems far from exhausted, as evidenced by regular publications.

The theory of survey sampling, which makes abundant use of the calculation of probabilities, attracted the attention of university statisticians and very quickly they reviewed all aspects of this theory that have a mathematical interest. A coherent mathematical theory of survey sampling was constructed. The statisticians very quickly came up against a difficult problem: surveys with finite populations. The proposed model postulated the identifiability of the units. This component of the model makes irrelevant the application of the reduction by sufficiency and the maximum likelihood method. Godambe (1955) states that there is no optimal linear estimator. This result is one of the many pieces of evidence showing the impossibility of defining optimal estimation procedures for general sampling designs in finite populations. Next, Basu (1969) and Basu & Ghosh (1967) demonstrated that the reduction by sufficiency is limited to the suppression of the information concerning the multiplicity of the units and therefore of the nonoperationality of this method. Several approaches were examined, including one from the theory of the decision. New properties, such as hyperadmissibility (see Hanurav, 1968), are defined for estimators applicable in finite populations.

A purely theoretical school of survey sampling developed rapidly. This theory attracted the attention of researchers specializing in mathematical statistics, such as Debabrata Basu, who was interested in the specifics of the theory of survey sampling. However, many of the proposed results were theorems of the nonexistence of optimal solutions. Research on the question of the foundations of inference in survey theory was becoming so important that it was the subject of a symposium in Waterloo, Canada, in 1971. At this symposium, the intervention of Calyampudi Radhakrishna Rao (1971, p. 178), began with a very pessimistic statement:

> I may mention that in statistical methodology, the existence of uniformly optimum procedures (such as UMV unbiased estimator, uniformly most powerful critical region for testing a hypothesis) is a rare exception rather than a rule. That is the reason why ad hoc criteria are introduced to restrict the class of procedures

> in which an optimum may be sought. It is not surprising that the same situation is obtained in sampling for a finite situation. However, it presents some further complications which do not seem to exist for sampling from infinite populations.

This introduction announced the direction of current research.

In survey sampling theory, there is no theorem showing the optimality of an estimation procedure for general sampling designs. Optimal estimation methods can only be found by restricting them to particular classes of procedures. Even if one limits oneself to a particular class of estimators (such as the class of linear or unbiased estimators), it is not possible to obtain interesting results. One possible way out of this impasse is to change the formalization of the problem, for example by assuming that the population itself is random.

1.7 Modeling the Population

The absence of tangible general results concerning certain classes of estimators led to the development of population modeling by means of a model called "superpopulation". In this model-based approach, it is assumed that the values taken by the variable of interest on the observation units of the population are the realizations of random variables. The superpopulation model defines a class of distributions to which these random variables are supposed to belong. The sample is then derived from a double random experiment: a realization of the model that generates the population and then the choice of the sample. The idea of modeling the population was present in Brewer (1963a), but it was developed by Royall (1970b, 1971, 1976b) (see also Valliant et al., 2000; Chambers & Clark, 2012).

Drawing on the fact that the random sample is an "ancillary" statistic, Royall proposed to work conditionally on it. In other words, he considered that once the sample is selected, the choice of units is no longer random. This new modeling allowed the development of a particular research school. The model must express a known and previously accepted relationship. According to Royall, if the superpopulation model "adequately" describes the population, the inference can be conducted only with respect to the model, conditional to the sample selection. The use of the model then allows us to determine an optimal estimator.

One can object that a model is always an approximate representation of the population. However, the model is not built to be tested for data but to "assist" the estimation. If the model is correct, then Royall's method will provide a powerful estimator. If the model is false, the bias may be so important that the confidence intervals built for the parameter are not valid. This is essentially the critique stated by Hansen et al. (1983).

The debate is interesting because the arguments are not in the domain of mathematical statistics. Mathematically, these two theories are obviously correct. The argument relates to the adequacy of formalization to reality and is therefore necessarily external to the mathematical aspect of statistical development. In addition, the modeling proposed by Royall is particular. Above all, it makes it possible to break a theoretical impasse and therefore provide optimal estimators. However, the relevance of modeling is questionable and will be considered in a completely different way depending on whether one takes the arguments of sociology, demography or econometrics, three disciplines that are intimately related to the methodology of statistics. A comment from Dalenius (see Hansen et al., 1983, p. 800) highlights this problem:

> That is not to say that the arguments for or against parametric inference in the usual statistical theory are not of interest in the context of the theory of survey sampling. In our assessment of these arguments, however, we must pay attention to the relevant specifics of the applications.

According to Dalenius, it is therefore in the discipline in which the theory of survey sampling is applied that useful conclusions should be drawn concerning the adequacy of a superpopulation model.

The statistical theory of surveys mainly applies in official statistics institutes. These institutes do not develop a science but have a mission from their states. There is a fairly standard argument by the heads of national statistical institutes: the use of a superpopulation model in an estimation procedure is a breach of a principle of impartiality which is part of the ethics of statisticians. This argument comes directly from the current definition of official statistics. The principle of impartiality is part of this definition as the principle of accuracy was part of it in the 19th century. If modeling a population is easily conceived as a research tool or as a predictive tool, it remains fundamentally questionable in the field of official statistics.

1.8 Attempt to a Synthesis

The "superpopulation" approach has led to extremely fruitful research. The development of a hybrid approach called the model-assisted approach allows valid inferences to be provided under the model but is also robust when the model is wrong. This view was mainly developed by a Swedish school (see Särndal et al., 1992). The model allows us to take into account auxiliary information at the time of estimation while preserving properties of robustness for the estimators in the event of nonadequacy of the model. It is actually very difficult to construct an estimator that takes into account a set of auxiliary information after the selection of the sample without making a hypothesis, even a simple one, on the relation existing between the auxiliary information and the variable of interest. The modeling allows a conceptualization of this type of presumption. The model-assisted approach allows us to construct interesting and practical estimators. It is now clear that the introduction of a model is a necessity for dealing with some nonresponse and estimation problems in small areas. In this type of problem, whatever the technique used, one always postulates the existence of a model even if sometimes this is implicit. The model also deserves to be clearly determined in order to explain the underlying ideas that justify the application of the method.

1.9 Auxiliary Information

The 1990s were marked by the emergence of the concept of auxiliary information. This relatively general notion includes all information external to the survey itself used to increase the accuracy of the results of a survey. This information can be the knowledge of

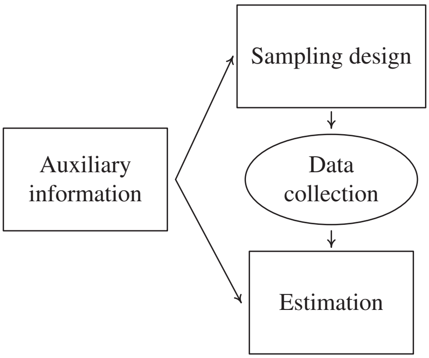

Figure 1.1 Auxiliary information can be used before or after data collection to improve estimations.

the values of one or more variables on all the units of the population or simply a function of these values. For most surveys, auxiliary information is available. It can be given by a census or simply by the sampling frame. Examples of auxiliary information include the total of a variable on the population, subtotals according to subpopulations, averages, proportions, variances, and values of a variable on all the units of the sampling frame. Therefore, the notion of auxiliary information encompasses all data from censuses or administrative sources.

The main objective is to use all this information to obtain accurate results. As shown in Figure 1.1, the auxiliary information can be used during the conception of the sampling design and at the time of the estimation of the parameters. When auxiliary information is used to construct the sampling design, a design is sought that provides accurate estimators for a given price or is inexpensive for given accuracy criteria. For these reasons, one can use unequal, stratified, balanced, clustered or multi-stage probability designs. When information is used in the estimation stage, it is used to "calibrate" the results of the census auxiliary information to the survey. The general method of calibration (in French, *calage*) of Deville & Särndal (1992) allows auxiliary information to be used without explicit references to a model.

Any sampling problem deals with how to use the available information. With the idea of auxiliary information, one frees oneself from the modeling of the population. This concept, which will be the main theme of this book, allows us to think of the problem of planning and estimation in an integrated way.

1.10 Recent References and Development

The books of precursors are Yates (1946, 1949, 1960, 1979), Deming (1948, 1950, 1960), Thionet (1953), Sukhatme (1954), Hansen et al. (1953a,b), Cochran (1953, 1963, 1977), Dalenius (1957), Kish (1965, 1989, 1995), Murthy (1967), Raj (1968), Johnson & Smith (1969), Sukhatme & Sukhatme (1970), Konijn (1973), Lanke (1975), Cassel et al. (1977, 1993), Jessen (1978), Hájek (1981), and Kalton (1983). These books are worth consulting because many modern ideas, especially on calibration and balancing, are discussed in them.

Important reference works include Skinner et al. (1989), Särndal et al. (1992), Lohr (1999, 2009b), Thompson (1997), Brewer (2002), Ardilly & Tillé (2006), and Fuller (2011). The series *Handbook of Statistics*, which is devoted to sampling, was published at 15-year intervals. First, a volume headed by Krishnaiah & Rao (1994), then two volumes headed by Pfeffermann & Rao (2009a,b). There is also a recent collective work led by Wolf et al. (2016).

The works of Thompson (1992, 1997, 2012) and Thompson & Seber (1996) are devoted to sampling in space. Methods for environmental sampling are developed in Gregoire & Valentine (2007) and for forestry in Mandallaz (2008). Several books are dedicated to unequal probability sampling and sampling algorithms. One can cite Brewer & Hanif (1983), Gabler (1990), and Tillé (2006). The model-based approach is clearly described in Valliant et al. (2000), Chambers & Clark (2012), and Valliant et al. (2013).

Many relevant books have been published and are still available in French. One can cite Thionet (1953), Desabie (1966), Deroo & Dussaix (1980), Gouriéroux (1981), Grosbras (1987), Dussaix & Grosbras (1992), Dussaix & Grosbras (1996), Ardilly (1994, 2006), Ardilly & Tillé (2003), and Ardilly & Lavallée (2017). In Italian, one can consult the works of Cicchitelli et al. (1992, 1997), Frosini et al. (2011), and Conti & Marella (2012). In Spanish, there exist also the books of Pérez López (2000), Tillé (2010), and Gutiérrez (2009) as well as a translation of the book of Sharon Lohr (2000). In German, one finds the books of Stenger (1985) and of Kauermann & Küchenhoff (2010). Finally, in Chinese there is a book by Ren & Ma (1996) and in Korean by Kim (2017).

Recently, new research fields have been opened. Small area estimation from survey data has became a major research topic (Rao, 2003; Rao & Molina, 2015). Recent developments in survey methodology are described in Groves (2004b) and Groves et al. (2009). Indirect sampling involves the selection of samples from a population that is not the population of interest but has links to it (Lavallée, 2002, 2007), for example new sampling algorithms have been developed to select balanced samples (Tillé, 2006). Adaptive sampling consists of completing the initial sample based on preliminary results (Thompson, 1992; Thompson & Seber, 1996). Capture–recapture methods are used to estimate the size of animal populations. Variations of these methods sometimes allow rare population sizes to be estimated or coverage surveys to be carried out (Pollock, 2000; Seber, 2002).

Resampling methods have been developed for finite populations (Shao & Tu, 1995; Groves, 2004b). Of course measurement errors will always remain a major research topic (Fuller, 1987; Groves, 2004a). Finally, substantial progress has been made in nonresponse methods: reweighting methods or imputation techniques (Särndal & Lundström, 2005; Bethlehem et al., 2011; De Waal et al., 2011; Kim & Shao, 2013).

One of the challenges that is currently emerging is the integration of data from multiple sources: administrative files, registers, and samples. In a thoughtful article entitled *Big data: are we making a big mistake?*, Tim Harford (2014) reminds us that the abundance of data is never a guarantee of quality. Access to new sources of data should not make us fall back into the mistakes of the past, as was the case during the 1936 US presidential election (see Section 1.5, page 6).

There have been methods for decades to integrate data from different sources. However, the multiplication of available sources makes these integration issues more and more complex. There is still a lot of research and development work needed to define the methods for integrating data from multiple sources by appropriately addressing the different measurement errors.