A new paradigm for Official Statistics?

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Abstract

Ready access to transactional data in real time challenges the authority of official series and the theories that underpin them. The discipline of data analytics, dedicated to detecting patterns and significant turning points within response times and resolutions that cannot be handled by present estimation methods, offers the prospect of meeting new demand for cross jurisdictional data series but without the authority of an official collection dedicated to the public policy process. The challenge is to reconfigure national statistics within the data deluge. Multivariate state space estimators that combine disparate sources of process data to repeated structured survey data efficiently offer such a foundation, but without abandoning the design paradigm of official statistics.

How is high quality, high cost, unit level information obtained from a sparse design-based sample frame to be combined with ‘short’ granular population views and ‘shoulder’ proxy sources in an optimal manner with calculable error structure? Given some theoretical solution that translates to the design tradition of official agencies how is this then to be accomplished in a survey environment of steeply rising cost and compromised quality? Knottnerus’ equivalence results suggest a way forward on both fronts by medium of the recursive restrictive estimator (RRE) class.

The potential of the recursive predictive method to deliver a satisfactory official estimation framework has been tested in two peripheral domains: natural resource monitoring and welfare payment assurance. The method, more generally, can ground data integration through theory that accounts for disparate sources of information, but respects quality assurance constraints.

Keywords: Kalman filters, micro integration, restriction estimators

1. Introduction

The task of an official statistician is changing. Building purpose-constructed collection frameworks backed by high profile censuses no longer drives work programs. This established order is being overshadowed by the search for authoritative inferential methods when augmenting expensive, carefully designed and executed, survey collections using administrative registers of reasonable quality (‘auxiliary data’) and cheap by-product transactional data (‘big’ or ‘proxy’ data) that have been captured in the course of government, social or commercial business with little or no discernible design, as remarked by Groves (2011) in his role as Director of the US Census Bureau.

National surveys grounded in sampling theory were developed through the 1930s and 1940s, operationalized from the 1950s and elaborated and qualified thereafter. In the absence of a register tradition they have come to be relied on as the principal source of official series even as production constraints and contested demands on them from a many faceted user community exposed their limitations. In consequence in such cases surveys are being reconceptualised as only one of several equipotent sources of data.

Administrative data, as Wallgren and Wallgren (2011) point out, already have come to play a more central role in the conceptualisation of official statistics. In the Nordic countries national collection agencies historically have had access to multiple linked registers for compiling statistics; the study of non-sample error and toward a coherent multi-source, design-based, theory has advanced there in consequence (Zhang's work with data fusion is a good example).

Broadening the collection base, preserving quality and improving responsiveness, are to be achieved within a standing budget constraint. So methods interest has moved from the absolute question: how to design a collection that can guide policy positions; to how to manoeuvre a variety of data-generating loci to meet emergent policy challenges.

Adapting the production of statistics in standardised formats within an increasingly strange external environment focussed attention from the 1990s, and excited methods activity in at least four directions: a) a renewed effort to harmonise concepts; b) a drive to bring models into estimation systems within deteriorating conditions for survey collection (cost and response); c) application of statistical discipline to database strategies as use of large data stores in a public decision environment was grasped; d) subjecting the activity of official statistical production to strictures of quality assurance. This flowering is manifest in international conferences, themed city meetings; and regional practitioner workshops initiated during the period in question.

Official statistics is evolving from a compendium of material collected under privilege and in a controlled statutory environment to be released at regular intervals as a quality guaranteed product, to an information system capturing transactions at far finer levels than previously envisaged in collection frameworks; the volumes more inchoate than in established databases; and coverage not respecting state boundaries of the activity in question. This opening reflects shifting social structure, geography or jurisdiction. At the same time deficiencies in accepted frameworks of inference have become apparent. Instrument integrity does not exclude the rich conditionality that exists between individual measures and a social or economic support.

Panel surveys have been used both for convenience, and to capture life course statistics (whether dealing with people or firms) and have as such been staple fare in the margin of official statistics. With rules for stochastic inference over time still primitive their rich covariance structure has been overlooked in estimates within the official record. The cross referencing of event histories of individuals, and institutional record keeping heightens interest in this medium for informing regulatory policies, and again suggests a state space formalism, amenable to the RRE construction.

Monitoring the national estate has entailed complex survey designs along with mapping methods, but is now being pushed to capture focal damage and incident effects beyond the reach of either ground or aerial surveys or remote sensing systems on their own. In microcosm the shifts in demand resemble the challenge to national offices: forest resource statistics are important to wood products industries, consulting foresters, forestry extension agencies and economic development agencies in local government, scientists and diplomatic cadre interested in climate change, legislative policy analysis services and a few legislators, and many mature environmental communities. These external publics often are at odds, but at least they can all trust the data for policy analyses.

Risk assurance in transfer payment accounting requires selected full entitlement reviews and access to administrative records – once again inference can be built by recursive incorporation of system information and expert observation. Movement away from regulation to risk is a general one and parallels this shift in the context in which official statistics is employed or demanded. This specialised application well illustrates the shape of new demand, and offers a practical demonstration of how it can be met.

2. How does this translate to methods?

Bringing disparate data sources together presents challenges to an official agency on a number of levels, not least an ethical one: to honestly reflect the reliability of a release, and to correctly weigh the contribution of disparate sources. This translates as methods challenges:

- How to infer across a continuous decision support where simple linear interpolation is no longer credible
- How to build series where what is of interest is not directly measurable using available instruments
- How to build an affordable and responsive information service that matches the dynamics of policy at a variety of levels of conception (topic, geography, legal statute, sociology, system of production)
- How to justify release of hybrid statistical information, equivalently how to assure credibility to published material – whether in summary (aggregated) form or in unit form or as a source for different avenues of release
- How to assign weight to different sources of correlated information – ranging from purposeful statistical design to transaction capture through scrapes.

It might equally be expressed as ‘build algorithms to…’ as expressed by Beulens and colleagues (2012). We interpret an algorithm as a method for extending stochastic design in time and space using resampling, Bayes theorem and nonparametric optimisation; or equally problem reduction using models and iterated numerical means.

A similar but more restricted set of challenges was faced in the 1980s as assumptions of sampling theory as laid down in the 1930s could no longer be sustained without auxiliary assistance. The theory of model-assisted survey sampling rebuilt confidence in official series even as the collection climate continued to deteriorate. The key restriction was in the undefined element of choice as to model, seen then as dictated by limited prior knowledge concerning the target population (the auxiliary or regressor element).

But data sources, well beyond the ability or resources of a national office to control, now compete with official series for attention and authority, even where their reliability is not tested against an established design. To retain such authority a recast of the theory enlarging the model-assisted paradigm to include newly available sources of data external to the agency, either concerning the target population, or standing in for collection themes (as designated) is called for, provided it has a design back bone.

We sketch a promising candidate extension and test it in practical applications.

2.1 The Recursive Restriction Estimator

The inspiration for tackling the problem in its full generality has come from results in Knottnerus (2003) specifically Chapter 12, building on the concept of model assistance expounded in Saerndal, et al (1992). Knottnerus demonstrates that generalised regression estimators are special cases of a new class of Restriction Estimator (RE) and its recursive extension (RRE). His figure 12.2 (p347) represents the key result. Knottnerus (2003) throughout emphasises the familial connection between Gaussian and Bayesian statistics, and systems theory and numerical analysis. It is the remarkable convergence in these results which gives credibility to the program as articulated in Beulens et al (2012).

The potential for state space methods for improving inference from repeated large scale surveys was recognised even before generalised regression estimation took hold. Key results were obtained by Tam and set out in chapter 5 of his doctoral thesis. These seem to have been largely overlooked in subsequent developments in model-based sampling inference that drew on material presented in the earlier chapters.

The RRE offers a solution to the problem of optimal prediction of an unobservable but estimable quantity in a granular environment generated by a continuous background process where there is a reasonable postulate of correlation between the manifold evolution and that of the probe (Czaplewski, 2010b).

On the one hand this formulation lends itself, as sketched below, to spatial analysis or process control; on the other it offers to transform the utility of official collections to deliver decision support for a wide class of policy questions, typically the subject of surveys, but leveraging the ubiquity of statistically commensurable by-product data, and parametral restrictions generated by prior knowledge and design.

The elements of this method are a) a panel, or repeated, survey (the probe) using a probability design that is time dependent, that is allowing the sample and the design to change in time; b) an independent, time flagged, source of auxiliary data defining a low dimensional, high accuracy, support for the probe; c) prior knowledge relating key indicator variables and process-driven (administrative, geographic, demographic, fiscal) rules; and d) frames for sampling and estimating surveyed quantities. The manner in which successive realisations of the probe and support system are composited will optimise final estimate efficiencies. The results apply equally to time series smoothing and to static calibration.

2.2 Total survey error

This would appear to be ignoring the compounding of intersecting measurement errors encountered in the drive toward data integration. Bakker (2011) asks in the absence of an overarching theory whether integrating source information at unit level can constitute a method at all. As remedy, Zhang (2012) offers a “2-phase life-cycle model of integrated statistical microdata” (p43 fig1), locating error in the different production processes and using an audit sample derived “probabilistic measure of individual discrepancy”.

Zhang extends the total survey error construction as it applies to the field effects of probability sampling in the public domain (articulated by Groves et al 2004), to error propagated by an administrative source and beyond that to error integrally across a variety of sources. For this the RE seems well adapted. Thus Zhang (p51) refers to *relevance error*, an analogue of system innovation, and later (p53) to "*misclassification errors* generating noise at the moment of production, which must be distinguished from the [signal]".

Czaplewski (2010b) has demonstrated advantage of RRE techniques in dual spatial survey-census data subject to misclassification. Interpreting 'empirical equivalence' (Zhang 2012 p56) as a step in recursive restriction estimation effectively repositions the microdata problem within the sample survey results of Knottnerus. The theory itself, coming from other contexts, is well established; what is surprising is the convergence on a set of basic results that adapt design based statistics to a multi-source environment. Below for clarity we give the basic elements in this construction.

3. Combining data sources using state space methods

A "state space" could be thought of as synonymous with a multivariate set of mutually dependent population parameters, where the number of parameters may be very large (e.g., cells or margins of statistical tables) with a hierarchical structure (e.g., sub-domains within a few larger sub-domains within even fewer and larger domains) and partitions for values at different points in time. These numerous variables are constants, we just do not know their exact values. The goal is to efficiently produce estimates of those values for this multivariate set of population parameters that are sufficiently accurate to acceptably reduce risk in informed policy decisions. That state space includes the set of study variables that supports substantive public policy analyses, plus a supplemental set of auxiliary variables that are not necessarily important to the analysis but are *inexpensively* known with high precision (perhaps known constants, such as remotely sensed pixel "maps") *and* correlated with the study variables.

3.1 Sample surveys

A sample survey is one type of instrument that can estimate the multivariate set of population values for the study variables. The values for auxiliary variables may be accurately associated with (registered to) each sample unit. Together, the study variables and the auxiliary variables may be termed a "state-space", which has an estimate of the associated covariance matrix.

The sample survey is a well-crafted instrument, analogous to a fine microscope that can study a few members of a population with considerable detail, i.e., multivariate measurement of sample units that supports estimates of multivariate population-level moments with known accuracy.

However, the sample survey is a very expensive instrument. There are other instruments that can inexpensively and precisely (often exactly) measure a sub-set of population parameters, which may be termed auxiliary variables. RRE constrains the corresponding set of sample-survey estimates (those from the microscope plus the registered auxiliary values) to exactly equal the very precise and inexpensive sub-set of auxiliary variables that are known precisely or exactly for the entire population.

If there are non-zero covariances among the study-variables and the auxiliary variables, then data-driven constraints on the auxiliary variables will improve the accuracy of estimates for the study variables, the degree of improvement being a function of the strength of the covariances.

High dimensional sampled observation translates imperfectly to population inference; the state space construction allows disparate elements to be combined in an orderly way.

3.2 Supported population inference

We wish to infer qualities of a population of statistical units evolving in time and within a given domain topology, that is a way of defining scope with rules for decomposition into sub-domains. While the topology is fixed, the boundary may evolve. The domain topology would support both administrative regions and sampling frameworks. Observations of the population come from a high dimensional unit probe repeated at (fixed or floating) intervals, and represented in the spatial domain by a time delimited probability sample. The probe collects signals of time and space continuous processes that affect the state of units of the population for the purpose of estimating the evolution of a population key decision indicator (in time).

To support the probe, a second data source collects low dimensional repeated measures of the population, or some activity of the population, but giving status insight through correlation with the probe variables. The probe and its support are linked by a model in the form of a contingency table that relates probability inference laws applying to the probe to auxiliary information, itself subject to measurement error.

In a first estimation phase this model is used in the sample design for the probe – optimal clustering, stratification and allocation of sample to strata. A second phase builds strength to the sample estimates in adjustment - to counter frame and field defects, and calibration. In a third phase the back history in model assisted estimation and the (quasi) continuous back history in the support are recursively combined to optimise characteristics of an estimator for extending inference to the entire support and projecting inference forward in time, alternatively at one point in time, recursively incorporating measure constraints. This step is carried out by use of a mathematical filter that mitigates high variability in the probe estimates at sub-domain levels, and bias predictions from the support series to the target indicators in a systematic, and in certain conditions optimal, way.

This method is well suited to dynamic graphical representation, and to advanced methods of estimate validation. Its generality makes it a candidate for a wide class of signal extraction applications common to official statistics. It addresses specifically the limitations imposed by rising cost to maintain survey quality, and the emerging availability of low cost universal transaction data alluded to in the introduction.

It operates for production of indicators, and internally for error estimation, representing data quality in terms of signal extraction and measure error filtering. Effectively it remains a design based method, but assisted by time series models supporting recursion (state space modelling in discrete time); and models for association (mapping) between a design-based estimation procedure and administratively generated auxiliary information on the population (generalised regression).

This approach conforms to and partly generalises the steps Zhang (2012) proposes to conceptualise and measure the statistical properties of integrated official data. It remains to build and demonstrate it in realistic settings. We sketch three cases where a solution on these lines is suggestive.

4. Applying Restriction Estimation

The cases sketched below illustrate how RREs can be applied to existing problems currently at the margin of official statistics, but likely to become more typical of the problems facing a national office under pressure to integrate official and unofficial data sources. It is suggested that they are reasonable candidates for a comprehensive solution, with natural extensions to small area and time series estimation. The full realization of this suggestion may be some way off; testing now underway points to fully constructible solutions.

4.1 Panel and Repeated Surveys

Consider a complex survey design to collect population information on one or more occasions from one or several samples of clustered units located in time (one or several waves) and space (stratified interpenetrating or overlapping clusters). The information is needed to support policy decisions concerning a topic of public interest. Represent this requirement as an ordered set of statistical indicators and attached reliance measures. Reliance measures are derived from an analysis of residuals to a generalised regression model of target variables against auxiliary information at the probe points,

The estimation apparatus incorporated in the survey design provides an initial value at points corresponding to the survey reference and those sub-domains for which reliable survey estimates can be obtained. It is desired to predict the values that target indicator set takes within a continuous support – typically forward to the present (it is unusual for probe reference points to coincide with reporting times) and beyond to a predictive near future, and to sub-domains appropriate to the policy situation (planning regions; basins of contagion etc.) with optimal variance/ bias properties attached to the predictor.

The probe is supported by an address register that gives accurate counts of a particular target domain: let us say low income households by household structure and residential location, updated fortnightly; together with some demographic and economic information. The correlation between target and auxiliaries is affected by sample error in the probe. The latter is bounded by the areal support allowed by the survey. It is used to wrap these correlations into the sample design (construction of frame, stratification, allocation of sample to strata) and estimation procedures and established benchmarks. This leaves out the error implied in the selection/ availability of support (coverage bias, lags, other response and scope limitations, cost).

A Bayesian recursion procedure produces a prediction model that extends beyond the point in time probe estimators, with formal properties. The system is refreshed historically, so that predictions from the model can be refined with each iteration of the probe. This recurrence predictor: a) builds strength from previous probes and continuous support evolution; b) draws attention to covariate models allowing for application in optimal designs and improved fixed point estimates; and c) allows dynamic predictions in space (subject to the domain topology defining the state vector) while remaining within a design framework, with a straightforward theoretical exposition.

The quality of estimates is conditioned by the availability and quality of the support. The predictive capacity of the filter, as measured by the covariance matrix relating auxiliary and target variables, is reflected in credibility properties of the indicators. Where the support assistance is concentrated at a point in time, and has low power in modelling performance (diffuse case), the restriction predictor reduces to the survey estimate with its limited inference capability. Where support variables span the dynamic predictive space the predictors assume (continuous) properties of the support itself. Between these extremes the predictor optimally combines the information from the probe and the support, improving on both as information sources.

4.2 Payment Process Control

The probe is a repeated stratified random sample survey of customers with annual refreshment of sample design, trimesterly field issue and data return, and quarterly public release. Model assistance (generalised regression) is used for published estimates. Calibration is against marginal totals (outlays and average customer numbers drawn from fortnightly accounting summaries). The series is supported by an administrative database of social security transactions, assembling customer characteristics typically required for determining eligibility for payment. The database is used in designing and drawing the sample and to link probe information to payment history (forwards and backwards). The performance indicator around which the series is built is *mispayment rate* (the consolidated discrepancy between what is paid and pay entitlement, represented as proportion of total outlay for performance monitoring and assurance purposes). This rate requires an elaborate survey apparatus to be accurately and consistently determined. The high cost of approaching individual customers and the low incidence of mispayment motivate optimally compositing survey and administrative information. Furthermore representing the target measure as a filtered time series makes the recasting of the problem from one of audit to one of statistical process control natural, and accessible to service managers, and policy analysts.

This apparatus incidentally allows a broader application to the health of the payments system as a whole – measuring performance against generally accepted social security objectives through using household structural information picked up in the probe – but not collected administratively - to extend the capacity of administrative data resource. This use suggests application to ad hoc customer surveys with more general topic coverage; and adds to the case of regular monitors of the customer population to evaluate attitudes, circumstances and capacities on and off payments. See (Horn 2008).

4.3 Forest Resource Estimation

The probe is a simple systematic sample of permanent population survey units (PSUs) on a 5-km grid that covers the entire USA, 120,000 of which reside in forests. Forest and tree-level field measurements are made for a 10-percent non-overlapping interpenetrating sub-sample each year. Each panel supports a design-unbiased estimator for indicators of forest condition and extent, with independent sampling errors among panels. The PSUs within each panel are re-measured every ten years such that decadal changes for each PSU are known. This permits design-unbiased estimates of decadal change from each panel.

In addition, remotely sensed imagery from space-borne satellites is available each year. These include pixel-level measurements of reflected multi-spectral light. The synoptic coverage is well suited for detection of changes in land use and catastrophic disturbances (e.g., large wildfires). While relatively rare at an annual time-scale and across extensive landscapes, these changes can be significant in aggregate, scantly represented in a sparse systematic sampling frame, and the subject of important analyses. The set of pixels fully covers the entire nation, and are thus, analogous to administrative information in surveys of human endeavours.

Forest dynamics have long been studied with assistance from deterministic process models, which predict annual changes in forest composition at the scale of an individual PSU. There has been a long history of deterministic econometric models that predict changes at broad landscape-scales driven by markets for wood products and competing land uses. While these models are often fit with PSU-level data from sample-surveys of forests, predictions from those models are rarely used to improve time-series of sample-survey estimates.

Presently, annual estimates for large areas take the form of a five-year moving average of estimates from the most recent five panels. All pixels within a single-date of remotely sensed imagery are categorised as either “forest” or “nonforest”; the geographic location of each PSU is registered to this imagery. Furthermore, each PSU is classified regarding its geopolitical membership (e.g., state, municipality), and these are cross-classified with the binary, remotely sensed, categories for post-stratification. Geopolitical post-stratification assures that area statistics agree with official census statistics.

While these methods are simple and robust, they do have limitations. In any dynamic landscape that is not at equilibrium, the five-year moving average suffers from lag-bias if the moving average is treated as an estimator of conditions during the terminal year. Analyses of changes over time are limited to measured changes for each PSU over ten years, and the moving average confounds interpretations of annual changes. Many cross-classified strata have few PSUs. Post-stratification precludes potential gains from many other sources of remotely sensed data, especially detection of rapid changes in land use and catastrophic disturbances. These simple methods are insufficient for reliable estimates for small areas using wealth of available auxiliary information.

Model-based estimators could gain strength from the aforementioned deterministic models. However, model-based estimators pose risks from prediction bias. Risk may be managed through judicious attention to residual differences between model predictions and unbiased sample survey estimates. Analyses of residuals can reveal patterns in model prediction errors. The resulting surprises can detect early symptoms of unexpected change and focus attention on subtle trends in poorly-modelled deterministic processes. More details are in (Czaplewski and Thompson 2008).

5. Discussion

The idea behind the recursive restriction estimator is not entirely new as it is equivalent to the multivariate composite indicator and a form of the static Kalman filter for which there exists a large literature. What is surprising is the natural way that it can be put to use to settle theoretical problems surrounding de facto hybrid estimation employed in official statistics. 20 years ago model-assistance brought auxiliary data into sample survey theory but left unresolved the cross over between sampling and measurement error. Rephrasing the problem in Bayesian terms it is possible to bring both sorts of error together in a unified theory, respecting design principles while allowing for extra design constraints outside of the sampling sphere.

Tradition within sample surveys imprints a perspective onto the sampling unit and mathematical functions of a sample of those units strongly centered on the univariate concept, which unintentionally conceives of a system as the mere amalgamation of separate and independent parts. On the other hand, engineering and econometric concepts focus on the status and dynamics of an entire interconnected system (a multivariate universe) with various instruments that imperfectly measure certain attributes and parts of that system. Cross-fertilization of these two different but compatible perspectives offers an opportunity for rapid improvement in sample survey applications.

The engineers have figured out the mathematics so it is left to formulate the problem from the system-perspective, and then apply those mathematical tools. It need not take a lot of new theory or development efforts. Indeed there is a direct algebraic identity between the multivariate composite estimator (static Kalman filter) and calibration estimators, and perhaps ratio and regression estimators. Derivation of the Kalman filter uses the “matrix inversion lemma”, which Maybeck (1979) gives on page 214. This lemma is the key to demonstrating the mathematical identity between the Kalman filter and more familiar sample-survey estimators.

By applying a multivariate Kalman filter to complement sample-survey methods for official statistics, we can derive a state space super structure appropriate to the unit integration of diverse sources, as explored by Bakker or Zhang. Numerical methods from electrical engineering are critical to the resolution of these systems of estimation in the production environments inspiring their work.

The robustness of the theoretical apparatus aside, these methods remain limited by availability of algorithms required for heavy duty matrix manipulations. Even here RRE has something to offer through its link to the Kalman filter: “the engineering perspective contributes essential solutions ... to numerical problems [that have] posed a stubborn obstacle to optimal estimation” Czaplewski op cit. In other developments – in this case in data linkage and automated edit and imputation - Winkler reports important progress in developing workable data matching and linking algorithms. It is not farfetched to imagine rephrasing the data linkage problem – until now largely computational, within the language of recursive restriction estimation.

References

Bakker, B. (2011). Microintegration, Statistical Methods paper (2011), The Hague/ Heerlen: Statistics Netherlands.

Buelens, B., Boonstra, H. J., van den Brakel, J., Daas, P. (2012). Shifting paradigms in official statistics, from design-based to model-based to algorithmic inference, Discussion paper (2012), The Hague/ Heerlen: Statistics Netherlands.

Czaplewski, R. L. and Thompson, M. T. (2009). Opportunities to improve monitoring of temporal trends with FIA panel data. In: McWilliams, Will; Moisen, Gretchen; Czaplewski, Ray, comps. Forest Inventory and Analysis (FIA) Symposium 2008; October 21-23, 2008; Park City, UT. Proc. RMRS-P-56CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Available at URL= http://www.treesearch.fs.fed.us/pubs/33362 (Accessed January 2013)

Czaplewski, R. L. (2010a). Recursive Restriction Estimation: An alternative to Post-Stratification in surveys of land and forest cover, Res. Pap. RMRS-RP-81. Fort Collins, CO: US Department of Agriculture Forest Service, Rocky Mountain Research Station. 32p.. Available at URL= http://www.treesearch.fs.fed.us/pubs/36116 (Accessed January 2013)

Czaplewski, R. L. (2010b). Complex sample survey estimation in static state-space, Gen. Tech Rep. RMRS-GTRR-239. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. 124p. Available at URL http://treesearch.fs.fed.us/pubs/36115 (Accessed January 2013)

Czaplewski, R. L., Thompson, M. T., Moisen, G. G. (2012). An efficient estimator to monitor rapidly changing forest conditions, pp 416-420. In Moving from status to trends: Forest Inventory and Analysis (FIA) symposium 2012. Eds Randall S. Morin; Greg C. Liknes,. Gen. Tech. Rep. NRS-P-105. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. [CD-ROM]. 478 p. Available at URL= http://treesearch/pubs/42307 (Accessed January 2013.)

Groves, R. M., Fowler, F. J., Couper, M., Lepkowski, J. M., Singer, E., Tourrangeau, R. (2004). Survey Methodology, New York: Wiley

Groves, R. M. (2011). The future of producing social and economic statistical Information, Directors Blog: US Census Bureau. Available at URL= http://directorsblog.blogs.census.gov/2011/09/08/the-future-of-producing-social-and-economic-statistical-information-part-i/ (Accessed January 2013)

Horn, S. (2008). Quality assurance surveys and program administration, Proc European Conf. Quality in Official Statistics: ISTAT. Available at URL=http://q2008.istat.it/sessions/7.html (Accessed January 2013)

Knottnerus, P. (2003). Sample Survey Theory – some Pythagorean Perspectives, New York: Springer-Verlag.

Maybeck, P. (1979). Stochastic Models, Estimation, and Control, New York: Academic Press

Saerndal, C. E., Swensson, B. and Wretman, J. H. (1992). Model Assisted Survey Sampling, New York: Springer-Verlag.

Tam, S. M. (1988) Chapter 5 in 'Estimation in finite population sampling: robustness and optimality', thesis, submitted for the degree of Doctor of Philosophy, The Australian National University. Available at: http://scholar.google.com/citations?view_op=view_citation&hl=en&user=YtMjNuYAAAAJ&cstart=20&citation_for_view=YtMjNuYAAAAJ:UebtZRa9Y70C

Wallgren, A. and Wallgren, B. (2011). To understand the possibilities of administrative data you must change your statistical paradigm! Proc. Section on Survey Research Methods Section, American Statistical Association. Available at URL= http://www.amstat.org/sections/srms/Proceedings/y2011f.html (Accessed January 2013)

Winkler, W. E. (2011). Cleaning and using administrative lists: Enhanced practices and computational algorithms for record linkage and modelling/ editing/ imputation, Proc. Section on Survey Research Methods Section, American Statistical Association. Available at URL= http://www.amstat.org/sections/srms/Proceedings/y2011f.html (Accessed January 2013)

Zhang, L.-C. (2012). Topics of statistical theory for register-based statistics and data integration, Statistica Neerlandica (2012) Vol. 66, nr. 1, pp. 41–63