



A digital twin of the Vosges forests to benchmark sampling strategies for forest inventory

Dynamic sampling and inference for a smart forest monitoring with applications to the French National Forest Inventory.

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Thematic actions concerned: WP2

Context —

The effects of global change and the loss of biodiversity are issues that entered the public and political spheres, and the awareness of the imprint of human actions increases expectations towards forests. These new expectations highlight the need to quantify and monitor not only the condition of forests but also their ability to support the provision of these ecosystem services.

However, large-scale inventory methods have been developed for resource monitoring and at a multi-annual timescale. New expectations, as well as more intense and frequent disruptions, require a review of these methods, to make them evolve towards greater responsiveness.

The sampling and estimation methods of the French national forest inventory were redesigned in 2004 with the aim of allowing annual coverage of the territory and adaptability of the sampling effort. The data collected over the past 15 years constitute an unequaled empirical basis, which should make it possible to assess the effectiveness and limits of current methods.

Moreover, the skills needed to analyze survey and estimation methods are extremely rare, particularly in the forestry sector. The premature disappearance of the pairs (Jean-Christophe Hervé, Adrian Lanz) leaves a deep lack in a very small community. The role of the project is to contribute to the renewal of these skills and to develop new sampling and inference strategies, by bringing together within the framework of the project people who can contribute with a specific and complementary experience.

Objectives —

The goal of the project is to develop survey methods, ranging from sampling to estimation, to respond to rapid modulation constraints of the sampling intensity, while maintaining high levels of precision. Although developed in the context of the national forest inventory, the general nature of these methods will be maintained and strengthened to allow them to be used in ecosystem surveys.

A first objective is to propose sampling methods for forest inventories, to describe and evaluate current post-stratified statistical estimators, and to compare them with existing estimators in critical contexts. A second objective is to evaluate and optimize forest stratification/post-stratification schemes with perspectives on variance-bias trade-off and small strata issues. A third objective is to redesign the sampling strategy of this inventory and increase its flexibility and independence.

Approaches —

The approach has two very complementary aspects: axiomatization and quantitative analysis. The axiomatization constitutes a formalization of the sampling and estimation methods of the national forest inventory. This formalization represents an effort to anchor inventory methods in the survey theory, and therefore represents an important theoretical prerequisite. This activity aims to provide the work with statistical foundations specific to the discipline, as well as a base of bibliographical references. The formalization also ensures that the underlying assumptions for the validity of the studied estimators are clearly stated and evaluated, and that the limit properties of the estimators can be derived. The quantitative analysis is based on the development of an exceptional database built from 20 years of surveys in the national forest inventory, and first, to carry out a critical quantitative analysis. The hypotheses and theoretical limit values will be compared with the ranges and variance of the empirical values collected during the fifteen years of operation of the inventory method.

Key results —

- A new framework for forest inventories was created, which enables to simulate a variety of sampling designs, and related estimation methods. The framework can support very complex sampling designs, which are currently used in National Forest Inventories throughout Europe. This includes two-stage sampling, e.g. when a tessellation is applied to the territory under study and cells are selected at the first-stage. This also covers two-phase sampling, which is of routine use in forest inventories.
- One important theoretical contribution is a framework combining two-stage and two-phase sampling. Under this framework, a tessellation is applied to the territory under study and cells are first selected at the first stage. At the second stage, a sample of points is selected in these cells, characterized by photo-interpretation, and a sub-sample may be selected by various sampling strategies and surveyed on the field. This strategy, although common in several NFIs, was not recognized nor formalized as such.
- The framework is a benchmark tools that allows to compare the sampling strategies and the efficiency of the sampling designs used by NFIs in EU and Northern America. It is the first time such NFI sampling and estimation simulator is made.
- Incorporate and test new sampling methods for NFIs. The framework was completed with sampling strategies that are currently not used by NFIs. This allows us to compare the efficiency of the current methods with new competitive ones, especially methods dedicated to more adaptivity in the sampling.

- Increase adaptivity in sampling designs. The framework developed allows to adapt the otherwise rigid grid-based sampling designs in order to modulate the sampling intensity in space and time, for instance in response to forest disturbances.
- Creation of a very large-scale digital twin of the Vosges forests (64 x 96 km). Building on the PhD by Ankit Sagar (directed by Cédric Vega), the digital twin is made of more than 83 million trees spatially positioned into 13,553 forest stands. The composition, tree diameter and height are strictly reflecting the measurements made by the NFI in this region. This digital twin allows to simulate whatever sampling design used in a NFI in Europe.

Main conclusions including key points of discussion —

- The work realized brought results in several critical domains, such as the survey sampling with theoretical contributions (combining two-stage and two-phase sampling for large-scale surveys), and forest inventory domain.
- The results of the simulation made within the proposed framework confirmed the unbiasedness of forest survey approaches, particularly noting that systematic sampling in the first stage results in smaller variances compared to simple random sampling with or without replacement. These results are particularly relevant to NFIs.
- The axiomatization of the French NFI, a major target in the PhD, was finalized and the framework developed allows to compare the current strategy with alternatives. The unbiasedness of the estimations was confirmed.
- The framework allows to test many options in the sampling and estimation methods. Choices need to be made because of the limited time available within the PhD.
- The efforts spent in the developing the (very complex) framework, with aspects related to theory and to its informatic implementation, have also slowed the publication of the results.

Perspectives —

- Alternative sampling and estimation methods can be proposed since the framework developed through the PhD will allow to simulate any particular sampling design, and thus to benchmark current and new designs.
- The framework is the first simulation tool for NFIs. With further development, it could be turned into a universal simulator that would encompass most sampling methods used in NFIs in the world. Such a universal tool would have a great impact if published, both as a way to benchmark methods, but also in the aim of harmonizing estimation, for instance throughout EU.
- The optimization of the French NFI is possible thanks to the framework developed, whereby a variety of changes in the sampling designs of the first stage or the second phase, in the stratification and post-stratification can be tested.

Valorization — (scientific: publications, book chapter, presentation at conferences...); economic: Soleau envelope, patent, license...; distribution: press release, interview...)

Conference:

1. Presentation at a conference

12th International french-speaking conference in survey sampling ; Location : Aubervilliers Campus Condorcet, Date: 22nd to 24th March 2023

Type: Oral Presentation

Titre : Formalization of the sampling design and of the estimators used in the French NFI

2. Presentation at a conference

Programme de la journée scientifique (Seminar of the SiReNa Doctoral School)

21st March 2023

Type: Oral Presentation

Titre : Sampling and estimation in French National Forest Inventory

3. Presentation at a conference (forthcoming, accepted)

26th IUFRO World Congress 2024 in Stockholm, Sweden

Type: Poster

Titre : An adaptive sampling and estimation method for National Forest Inventory to monitor the disturbances

Articles:

1. Duong T, Bouriaud O, Chauvet G. A new framework for spatial surveys of natural populations.

Submitted to Survey Statistics and Methodology, in revision.

2. Bouriaud O, Brion P, Chauvet G, Duong T, Pulkkinen M. The weight share method in forest inventories: refining the relation between points and trees.

Submitted to the Canadian Journal of Forest Research, in revision.

Leveraging effect of the project—

The domain of survey sampling is extremely specialized, representing very few people. Forest inventories deal with specificities that make them even more specialized: spatial survey, continuous populations, indirect sampling. Thus, the investment in the PhD represents a strong contribution to a highly valuable and rare field of competences.

The PhD has been an opportunity to bring in specialists working in different domains and to synthesize knowledge in order to push the frontiers.

The theoretical and simulation works undergone in the PhD has important consequences to other research activities related to the monitoring of forests. For instance, the efforts spent to formalize the methods of the French NFI are of direct importance for the research activities in the multi-source forest inventory (C. Vega, J-P Renaud, C Piedallu).