

### Long-term EXPansion of the FrEnch foRests: causal processes and Tools to support Sustainable Forest Management

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**Context** — After centuries of decrease, the forest area of most developed European countries has been increasing since the industrial revolution, a phenomenon termed “forest transition”. While current increase in growing stock (GS) is greater than that in area, it remains far less studied, which at least stems from the lack of ancient data prior to implementation of national forest inventory (NFI) programs. It is therefore essential to assess these changes, to decipher their variations and underlying causes, and to try to quantify them over the longer term in order to locate current forest resources on a broad trajectory and to anticipate their future dynamics.

**Objectives** — (1) A first objective was to inquire and quantify forest areal, GS and GS density (GSD) changes and their spatio-temporal variations over 40 years (1975-2015), a period covered by the NFI program. (2) A second objective was to uncover the processes of GS changes and to quantitatively split the GS expansion magnitude across dynamically-homogeneous forest ensembles. (3) The third objective was to locate the actual GS expansion in a secular perspective. This analysis consisted in reconstructing the GS chronology since 1850.

**Approaches** — Analysis are mainly based on NFI data (since 1961). (1) Area and GS changes were related to geographical contexts, ownership of property and species composition, as factors hypothesized to feature forest changes for forest management and policy and land-use reasons. We screened for changes in the rate of expansion. The relationships between GS changes and some forest attributes (initial GS and GSD, recent forest area increase) were investigated using regression modelling. (2) The study of the processes of GS changes was based on GS flux estimation (growth, ingrowth, mortality and harvest) systematized across a forest partition based on geography, ownership and species composition. Methods of data analysis (PCA and clustering) were used in order to identify these forest ensembles and assess their dynamics. (3) In order to reconstruct the secular expansion, levels of GS in 1892, 1908 and 1929 (associated to area of agricultural statistics and ‘Daubrée’ forest statistic) were estimated using a conditional imputation approach for GSD estimation (mean and quantiles) based on NFI data. Then, a holistic and area-dependent growing stock densification model was implemented to inquire the conditions required on densification patterns and magnitude to simulate the reconstituted GS chronology. A sensibility analysis on the initial conditions in 1850, the areal evolution, and the densification model was conducted.

#### **Key results** —

Objective 1:

- Between 1975 and 2015, GS increases were three times faster than the areal ones, underlining the intensity of forest densification. No sign of saturation was found. Private forests, and mainly broadleaved ones, presented the greatest GS and GSD increases, suggesting the essential role of natural expansion and agricultural land abandonment.
- Regression models revealed the positive effect of initial GS and of recent areal increases on GS expansion together with a weak negative effect of GSD, increasing over time.

Objective 2:

- The analysis of GS expansion processes evidenced the generally low level of harvests in comparison to forest growth, and the contribution of recent forests to wood resource development.
- It led to identify 4 synthetic forest ensembles contributing to the expansion and of distinct dynamics, mainly composed of private and communal forests. Public forests, essentially broadleaved ones in lowlands and mid-

elevation mountains presented a decreasing part in the total GS, accounted for by intense harvests in these forests, and an anecdotal contribution to the expansion.

#### Objective 3:

- It suggested a very low mean GSD at the beginning of the period (25 m<sup>3</sup>/ha), and a plausible GS increase by almost +300% (> 700 hm<sup>3</sup> in 1908 against 2 500 hm<sup>3</sup> currently), underlying the importance of this expansion.
- Singularly, a convex growth model over 150 years (initial phase of a sigmoid Hossfeld model) was required to correctly simulate historical forest densification, attesting of a significant inertia in wood resource reconstitution after the forest transition. This was interpreted based on a gradual decrease in harvest rates for which indices were collected, or to a gradual recovery of site fertility.
- The analysis also suggested a distinct kinetics for GS densification in plantation forests.

*Main conclusions including key points of discussion* — These researches reveal the magnitude of GS expansion and the importance of its analysis across forest contexts. This ancient expansion, resulting from low levels of harvests, does not present any current sign of saturation and constitute a persistent carbon sink which should not decrease in the next decades assuming similar contextual conditions. According to the process analysis of GS expansion, a significant fraction of the GS increases does not constitute readily available additional wood resources as it relies on recent forests or hardly accessible forests. Thus, future harvest intensification policies must be contextualized and evolving in time.

#### **Valorisation —**

##### *Articles :*

DENARDOU, Anaïs, HERVÉ, Jean-Christophe, DUPOUEY, Jean-Luc, BIR, Jean, AUDINOT, Timothée, BONTEMPS, Jean-Daniel. *L'expansion séculaire des forêts françaises est dominée par l'accroissement du stock sur pied et ne sature pas dans le temps. Revue Forestière Française, 2017.*

DENARDOU, Anaïs, DUPOUEY, Jean-Luc, HERVE, Jean-Christophe, BIR, Jean, MORNEAU, François, BONTEMPS, Jean-Daniel. *Unprecedented contemporary (1976-2014) increase in the growing stock of French forests is persistent and dominated by private broadleaved forests. European Journal of Forest Research (soumis)*

DENARDOU, Anaïs, DUPOUEY, Jean-Luc, HERVE, Jean-Christophe, AUDINOT, Timothee, BONTEMPS, Jean-Daniel. *Reconstituted increase in the growing stock of French forests since 1850 reaches +300% and requires non-saturating forest densification assumption. (en préparation)*

##### *Communications orales :*

*Séminaire conjoint BGF-REACTIF (GIP Ecofor et ADEME ; mars 2016) : Denardou, A., Dupouey, J.L., Bontemps, J.D. L'expansion séculaire des forêts françaises : analyse des facteurs de gestion à l'œuvre et simulation par un modèle de dynamique forestière à large échelle.*

*Journées de la recherche IGN (mars 2017) : Denardou, A., Dupouey, J.L., Hervé, J.C., Audinot, T., Bontemps, J.D. L'expansion à long terme des forêts françaises : une analyse exploratoire à partir des données de l'inventaire forestier national*

*Colloque IUFRO (septembre 2017) : Denardou, A., Audinot T., Dupouey J.L., Hervé J.C., Bontemps J.D. Long-term expansion in the growing stock of the French forests : analysis and modelling*