Annals of Forest Science (2018) 75: 48
https://doi.org/10.1007/s13595-018-0692-z

REVIEW PAPER

GIS Coop: networks of silvicultural trials for supporting forest management under changing environment

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Received: 17 July 2017 / Accepted: 10 January 2018 / Published online: 9 April 2018

Abstract

• ***Key message*** **The diversity of forest management systems and the contrasted competition level treatments applied make the experimental networks of the GIS Coop, a nationwide testing program in the field of emerging forestry topics within the framework of the ongoing global changes.**

• ***Context*** To understand the dynamics of forest management systems and build adapted growth models for new forestry practices, long-term experiment networks remain more crucial than ever.

• ***Aims*** Two principles are at the basis of the experimental design of the networks of the Scientific Interest Group Cooperative for data on forest tree and stand growth (GIS Coop): contrasted and extreme silvicultural treatments in diverse pedoclimatic contexts.

• ***Methods*** Various forest management systems are under study: regular and even-aged stands of Douglas fir, sessile and pedunculate oaks, Maritime and Laricio pines, mixed stands of sessile oak, European silver fir, and Douglas fir combined with other species. Highly contrasted stand density regimes, from open growth to self-thinning, are formalized quantitatively.

• ***Results*** One hundred and eighty-five sites representing a total of 1206 plots have been set up in the last 20 years, where trees are measured regularly (every 3 to 10 years). The major outputs of these networks for research and management are the calibration/

This article is part of the Topical collection on Mensuration and modelling for forestry in a changing environment.

Handling Editor: Thomas Wohlgemuth

Contribution of co-authors

Ingrid Seynave designs and manages database, coordinates the works on the network sampling scheme and the acquisition of ecological data, analyzed data, and coordinated and wrote the paper. Céline Meredieu co-coordinated the paper. Thomas Cordonnier, Céline Meredieu, Sandrine Perret, Claudine Richter, and Priscilla Cailly coordinate one of the networks (respectively, mixed stand, Maritime and Laricio pine, Laricio pine, Oak, and Douglas fir), analyzed data, and co-wrote the paper. Christine Deleuze, Dominique Merzeau, and Eric Paillassa represent their organization in the GIS Coop, and checked and corrected the paper. Alain Bailly and Christian Ginisty coordinate the GIS Coop and supervised the paper. Jean-François Dhote coordinated the GIS Coop and supervised the paper. Philippe Balandier, Jean-Daniel Bontemps, and François Lebourgeois designed and supervised research project using GIS Coop networks and co-wrote the paper.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s13595-018-0692-z) contains supplementary material, which is available to authorized users.

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validation of growth and yield models and the drawing up of forest management guides.
• ***Conclusion*** The GIS Coop adapts its networks so that they can contribute to develop growth models that explicitly integrate pedoclimatic factors and thus also contribute to research on the sustainability of ecosystems under environmental and socio-economic changes.

Keywords Long-term silvicultural trials · Growth and yield models · Database · France · Forest management · Competition

1 Introduction

The ongoing and upcoming environmental changes and the diversification of wood uses (IPCC 2014) have deeply influenced forest management goals in the last decades; forest managers aim to define new forestry practices that combine technical efficiency, economic and environmental performance, and resistance and resilience to disturbances (D'Amato et al. 2011; Doley 2010; Evans and Perschel 2009; Legay et al. 2007; Lindner et al. 2010; Maciver and Wheaton 2005; Parks and Bernier 2010; Seidl et al. 2011). Forestry options are numerous: it is possible to shorten the rotation length so as to lower risks (Albrecht et al. 2015), adapt the frequency and intensity of thinning to decrease water needs (Aldea et al. 2017; Gebhardt et al. 2014; Guillemot et al. 2015; Martin-Benito et al. 2010; Primicia et al. 2013; Sohn et al. 2013; Trouvé et al. 2017; Van Der Maaten 2013), use other species, varieties, or improved materials, favor mixed or uneven stands supposed to be more productive (Pinto et al. 2008; Pretzsch et al. 2010; Pretzsch et al. 2013; Vallet and Pérot 2011), and more resistant to both biotic attacks (Jactel et al. 2012; Perot et al. 2013) and drought (Lebourgeois et al. 2013; Metz et al. 2016).

These evolutions prompt us to examine the tools available to plan and implement forestry practices and meet these new environmental, economic, and social objectives. The first yield tables were published in the 1960s (Assmann and Franz 1965; Décourt 1964; Hamilton et Christie 1971). They present the values of all the main growth and yield variables for a sequence of stand ages of even-aged stands depending on the fertility of the site. Numerous tree species were taken into account, but only a limited number of silvicultural treatments. In the years 1980–1990, numerous empirical growth models were developed (Franc et al. 2000; Houllier et al. 1991; Porté and Bartelink 2002; Pretzsch 2009), especially in France for the main production species: European beech (Dhôte 1991), sessile oak (Le Moguédec and Dhôte 2012), Laricio pine (Meredieu 1998), Maritime pine (Lemoine 1982), black pine (Dreyfus 1993), Norway spruce (Pain and Boyer 1996), and Douglas fir (Bailly 1997). Finally, process-based growth models integrating forest management modules aimed at simulating the effect of silvicultural treatments were developed (Courbaud et al. 2015; Guillemot et al. 2014, 2015; Pretzsch et al. 2008). Whatever the model type, the availability and the characteristics of databases to fit or validate the models remain fundamental, as they determine most of the domain of validity of the models (Burkhart and Tomé 2012).

Forestry experiments and observations encounter strong constraints. Mainland France encompasses four biogeographical zones (Atlantic, continental, alpine, Mediterranean) out of the nine zones recorded in Europe and displays a substantial diversity of shrub and tree species (more than one hundred and fifty species including twenty-four main ones devoted to production according to the IGN (National Geographic Institute), with diverse functional traits (broadleaved or coniferous species, with deciduous or evergreen foliage) (Aubin et al. 2016). Additionally, the diversity of forestry practices induces spatial and temporal variability in the structure of forest stands. Besides, the longevity of trees requires long-term trials and monitoring, all the more so as forest managers are as interested in the short-term response of trees to forestry operations (clearing the undergrowth, thinning…) as in their effect on the total production of a stand from regeneration to final harvesting.

Long-term forest monitoring design can be classified into four categories (Table 1): networks composed of sites instrumented with probes and sensors, experimental networks, observation networks, and national forest inventories. The first are heavily monitored observation sites; as a consequence, their number and thus the representativeness of the targeted ecosystems are limited. At the opposite end of this classification, forest inventories do not require permanent sensors/near real time data collection and do not manipulate ecosystems. Thanks to the number of plots in the inventory; they make it possible to be representative of the forest resource and investigate a large part of the environmental range and diversity of forestry practices across a geographic region. Most of the time, they are measured once or twice (for example, the monitoring of the French National Forest Inventory plots provides two measurements with an interval of 5 years between each; see also Tomppo et al. 2010). However, as for observation networks, they do not test forestry treatments. Forestry trial networks are designed to find out the relationship between stand growth, stand conditions, and stand treatments that are purposely manipulated and undergo regular

Table 1 Network typology

Network type	Ecosystem representativeness	Environmental data	Manipulative experiments	Examples, references
National Forest Inventory	+++	+	0	Tomppo et al. 2010, Leban and Bontemps 2016
Experimental networks	++	+	+++	Forestry:
				Trial plot network (Pretzsch 2009)
				ALTER (Collet et al. 2015)
				TreeDivNet (Verheyen et al. 2016)
				Afocel's network (Gastine et al. 2003)
				GIS Coop (this article)
				Forest genetics:
				REINFFORCE (http://reinfforce.iefc.net/)
				PLANTACOMP (Anger et al. 2010)
				Soil fertility:
				MOS (Akroume et al. 2016)
				LTSP (Powers et al. 2005)
Monitoring networks	++	++	0	Renecofor (Ulrich 1995, Nicolas et al. 2014)
				ICP Forest (Rautio et Ferretti 2015)
				RAINFOR (Malhi et al. 2002)
In situ heavily instrumented sites	+	+++	+	FACE experiment (Rogers et al. 2006)
				ICOS (www.icos-ri.eu)
				SOERE F-ORE-T (http://www.gip-ecofor.org/f-ore-t/index.php)

Four forest network types can be distinguished depending on size and collected data. Their characteristics according to four criteria are indicated by "+" signs. "0" means that the network type does not manipulate ecosystems most of the time. For experimental networks, 3 sub-types (forestry, genetics, and soil) are distinguished depending on factors studied

(annual to pluri-annual) monitoring. They ensure (i) at the very least a good representation of the factors to be tested and (ii) the disentangling of factors, which are often correlated in observation networks.

The first forestry trials were set up as early as the late nineteenth century (Oudin 1930; Pretzsch et al. 2014; von Ganghofer 1881). Depending on their objective, a range of treatments is manipulated: planting density, species composition, fertilization, intensity, and frequency of thinning (Pretzsch 2009). Their shared objective is to quantify the impact of these factors on the growth and production of forest stands. These trials can be organized under the form of multi-local networks, i.e., a coherent set of experimental sites, to encompass a range of station contexts. Such networks exist in many countries: in Europe (France, Germany, Denmark, Sweden, and Finland) (Bédéneau et al. 2001; Herbstritt et al. 2006; Mäkinen 1999; Nilsson et al. 2010; Pretzsch et al. 2014; Vanclay et al. 1995), in North America (Curtis et al. 1997; Maguire et al. 1991), and in New Zealand (Hayes and Andersen 2007). To understand the dynamics of forest management systems and build adapted growth models for new forestry practices, long-term experiment networks remain more crucial than ever (IUFRO News 2017).

In North America, the idea of pooling resources from different private or public organizations involved in management or research in order to study forest yield is old and has led to the setting-up of cooperatives (Curtis et al. 1997; Maguire et al. 1991). These cooperatives are varied in their objectives (species, geographical zones, and forestry practices) as well as in their mode of functioning. To our knowledge, the Scientific Interest Group Cooperative for data on forest tree and stand growth (GIS Coop) is the only cooperative devoted to forestry trials in Europe to be managed by members of a partnership. The objective of this cooperative, which gathers seven research and development organizations (AgroParisTech, CNPF-IDF, CPFA, FCBA, INRA, Irstea, and ONF) and is supported by the French Ministry in charge of forests, is to build forestry trial networks and collect data to analyze and model the growth of trees and forest stands. The final aim is to improve management, especially by integrating these models into simulation platforms, as in, e.g., the "CAPSIS" platform (Dufour-Kowalski et al. 2012). These tools allow comparing different management alternatives (Courbaud et al. 2001; de Coligny et al. 2010; Meredieu et al. 2009) at the spatial scale of the stand and at the temporal scale of a rotation. These models and this simulator (http://capsis.cirad.fr/capsis/

models) have contributed to the publication of numerous forestry guides in France (Abt 2014; Angelier 2007; Chabaud and Nicolas 2009; Gauquelin and Courbaud 2006; Jarret 2004; Ladier et al. 2012; Sardin 2008, 2012a, b, 2013; Sardin et al. 2013).

Since the GIS Coop was created in 1994, three important choices have been made. The first choice was to investigate the response of trees and stands to various levels of competition, focusing on a few production species. Therefore, the main factor to be tested is the growing stock of stands, from regeneration to final harvesting, with extreme silvicultural treatments (from self-thinning to open growth stands). The second choice was methodological and responded to the weakness observed in the pre-GIS Coop networks which were often confined to a restricted geographic region where the species were dominant in forest resource. The GIS Coop networks investigate the whole production zone of the forest management system under study to analyze broad ranges of soil and climatic conditions. These choices ensure a wide validity domain and good robustness of the models and simulators with respect to the accuracy of responses to the simulated forest management alternatives. Last of all, environmental changes and the evolution of forestry practices led to a third important choice that consisted of installing experimental sites continuously and regularly over time. This strategy aims at disentangling age effects from date effects (Dhôte and Hervé 2000; Bontemps et al. 2009), an essential step for studying productivity changes in the context of global changes and at integrating new forestry practices such as the introduction of improved varieties.

This article aims to (1) describe the experimental project of the GIS Coop, (2) present the networks and the currently available data, and (3) show how the GIS Coop networks evolve so as to meet the new emerging needs related to the present environmental and economic changes.

2 GIS Coop experiment

2.1 Forest management systems

The forest management systems were mainly selected based on their economic interest and their relative abundance in the French forest landscape. Four networks were set up in pure (50% of the French forest is made of monospecific stands, Morneau et al. 2008) stands of Maritime pine (*Pinus pinaster* Aiton), Douglas fir (*Pseudotsuga menziesii* Mirb.), Laricio pine (with the two varieties: Corsican pine: *Pinus nigra subsp. laricio var. Corsicana* (Loudon) Hyl. and Calabrian pine: *Pinus nigra subsp. laricio var. Calabrica* (Loudon) C.K.Schneid.), sessile or pedunculate oaks (*Quercus petraea* Liebl. or *Quercus robur* L., respectively; sessile and pedunculate oaks trials are managed together). These five species are mostly managed in the form of even-aged stands in France. The species mentioned above are respectively the most harvested conifer species (6.1 Mm^3/year, NFI), the most productive species (17.2 m^3/ha/year, NFI), the third most common reforestation species (after Maritime pine and Douglas fir), and the first and second most common broadleaved species in terms of surface (777,000 and 72,000 ha, NFI).

A fifth network is being set up recently to study mixed stands. It will target the stands composed of two species, which represent 34% of forest area in France (Morneau et al. 2008). More particularly, three even-aged mixtures based on sessile oak (sessile oak-Scots pine, sessile oak-pedunculate oak, and sessile oak-European beech) and three uneven-aged stands based on silver-fir (silver fir-Douglas fir, silver fir-European beech, and silver fir-Norway spruce) are studied. These mixtures are among the most important ones in France: the oak-beech forest is the first broadleaved species mixture in terms of volume (150 Mm^3), the oak-pine forest is the first broadleaved-conifer mixture (420,000 ha and 60 Mm^3), and the silver fir-Norway spruce forest is the second most important coniferous species mixture in terms of surface (80,000 ha) (Morneau et al. 2008). This network also includes Douglas fir-European larch plantations because this rare mixture in French forest resource constitutes an alternative forest management system for a very productive species.

The species under study strongly differ in their distribution areas (indigenous vs. naturalized species), ecology (especially in terms of drought resistance and light requirements), and life traits (e.g., longevity or growth rates). The choice of these systems also makes it possible to contrast (natural vs. artificial) modes of regeneration and varying intensities of partial harvests during the life course of the stand.

2.2 Experimental design

The objective is to collect data for fitting/validating models of forest dynamics to define and support current or future forest management practices. To meet this objective, the networks were set up based on a number of general specifications drafted by all the GIS Coop partners (Table 2). These guidelines provide the size of networks, the choice and composition of experimental sites, and monitoring duration. The way these specifications have been applied in each system is described in Table 3.

The experimental design based on the "disjunct experimental plots" (Pretzsch 2009) was selected according to nested organization levels: an among-stand level to cover the ecological gradients of the national production area, a stand level to

Table 2 Experimental principles defined in the general specification of the GIS Coop. For each principle, implementation is specified through quantitative criteria

Experimental principles	Application
Multi-site network	Several dozen sites: distributed across the whole production area of the forest management system, encompassing the largest array of stations possible
Homogeneous sites at the station level	Evaluation criteria defined for each forest management system: based on site classification, completed by an inventory of indicator species and/or soil auger borings
Priority to the diversity of intra-site treatments	Per site: at least 3 plots submitted to different stand density regimes
Large plots for treatments and measurements	Pre-defined surface, so as to have at least 25 stems within the measurement zone at the end of the rotation, + a buffer zone at least 8 m wide to limit border effects
Individual tree measurement and compulsory measurement just before thinning	All stems as soon as the tree density is below a value (see Table 3)
	Systematic measurement campaign just before a thinning determined by the protocol and a monitoring just after
Duration of monitoring	One rotation: from installation (planting or from the date when trees reach 4-m height for the stands issued from natural regeneration), until final harvest, possible monitoring of a second rotation

test the factors to be studied, and a "tree in the stand" level as the unit of measurement. Thus, the main sources of the variability of the dynamics of trees and stands are taken into account, from the tree variability to the large-scale environmental variability (climate, forest). The setting-up of permanent plots monitored over the long term (over one or even two rotations) and measured regularly (every 1 to 10 years) provides data on the biological increment but also on other processes such as recruitment/regeneration, mortality, and harvestings.

These different spatial and temporal scales allow to calibrate/validate models that integrate the rotation of the stands and the different sources of variability. Beyond this first objective, they allow studying highly diverse, integrative questions such as the evaluation of a production sector (Bilot 2015) or finer ones such as the effects of climatic variability on tree individual growth (Trouvé et al. 2014, 2015).

The stand age is a key driver of growth. In a context of climate change, disentangle age and date effects may be very important to better model, for example, long-term growth (Bontemps and Esper 2011) or allometric equations (Genet et al. 2011) or to improve our understanding of carbon storage at tree and stand scales (Genet et al. 2009) and climatic signals in tree ring (Esper et al. 2008). To ensure that age remains orthogonal to date, the GIS Coop decided to space out the trials installations and to maintain the same tested silvicultural treatments over time. That will allow in the long term to achieve a distribution of all stand ages across all sampling years and thus to de-correlate stand age from measurement dates. This is essential for facilitating a clean assessment of each factor independently and for studying growth changes in a context of climate change.

That the experimental design and specifications are common to all the systems additionally ensures a strong coherence among the different networks. This coherence has technical advantages such as the opportunity to develop shared data collection tools and a database of a common structure. It is also of great scientific interest because it makes it possible to encompass several forest management systems within comparative studies (Trouvé et al. 2014).

2.3 Silvicultural treatments

2.3.1 A main factor: the competition level

A main factor was experimentally manipulated in all forest management systems, namely, stand density and its evolution from planting/regeneration to harvesting. This factor is related to competition among trees and to growing stock at the stand level. It is a key factor of regeneration, tree and stand growth, and mortality processes. Some studies performed at large scale have shown that this factor is the first determining factor of production, often ahead of pedoclimatic conditions and development stages (Trouvé et al. 2014, Trouvé 2015). Controlling stand density is one of the main tool foresters have at their disposal to adapt stand growth to the site conditions and to production objectives.

The GIS Coop imposed the use of a quantitative measure with maximum ranges to define the stand density regimes and to control their applications in the field. This quantitative formalization ensures greater homogeneity and stability when this factor is applied; this is particularly important in the case of multi-partner, long-term monitored networks. The choice of the scale for monitoring the stand density was based on

Table 3 Details of the experimental principles for each forest management system

		Sessile and pedunculate oaks	Douglas fir	Maritime pine	Laricio pine	Mixed forest
Experimental design	Targeted number of sites/plots	30/120	30/150	150/450	25/100	12/60
	Number of plots per site	3 minimum	3 minimum	3 minimum	3 minimum	5 minimum
	Surface of the measured plots (100 m^2)	36	15–25	10–25	10–25	30–70
Factors tested/controlled	Main factors tested	Density	Density	Density Improved genetic level	Density	Density Mixture rate
	Stand density index	RDI (Relative Density Index, Reineke 1933)	Number of trees per hectare	Lemoine's competition index (1991)	Hart-Becking's spacing factor	Even-aged stands: RDI Uneven-aged stands: Basal Area per hectare or Stand Density Index (Shaw 2000)
	Number of treatments for the density factor	6	9	9	10	3
	Secondary factors tested	None	None	Intensification of culture Soil preparation Phosphate fertilization	None	Spatial structure of the mixture
	Controlled factors	Stand regeneration (planting/natural regeneration)	Genetic origin	Pruning height of living branches	Variety (Corsica/Calabra)	None

previous research results to favor age- and fertility-independent indices (Table 3 and Annex 1). The stand density index selected is the one used in the empirical growth models developed in France in the 1990s. For sessile oak, Maritime pine, and Laricio pine, the index are respectively the Relative Density Index of Reineke (RDI, Le Moguédec and Dhôte 2012), the Lemoine's competition index (Lemoine 1982), and the Hart-Becking's spacing factor (Meredieu 1998). The calibrated RDI for sessile oak is also selected for pedunculate oak. At the contrary, the simplest index "number of trees per hectare" is still used for Douglas fir. To give an overview of variability of the stand densities observed, the range was calculated with the Hart-Becking's spacing factor which can be calculated for every species and do not need specific calibration (Table 6). Furthermore, to allow comparisons in this paper, the stand density regimes are grouped into seven categories to harmonize the presentation of the networks (Annex 1).

To cover the maximum range of competition, special efforts were made to define stand density regimes that ensured (i) maximum competition among trees characterized by cases of natural mortality (termed self-thinning), and (ii) at the opposite end, an absence of competition among trees (called open-growth). Intermediate regimes maintain stands within a given competition range throughout the whole rotation. Finally, regimes involving variable, decreasing and increasing competition levels, lead stands from a maximum competition level to a no-competition level, and vice versa (Annex 1). Whatever the parameters, the absence of competition is considered to be reached if the distance between trees is at least equal to their height. In certain systems, some stand density regimes go beyond that threshold, considered as a minimum. "No-competition" regimes and regimes with a variable competition level cannot be applied in forestry management because they lead to strong production losses and to major difficulties in their implementation related to the management of understory. But they are indispensable in trials to ensure the calibration/validation of models of stand dynamics in order to be used to investigate new management alternatives. "Open growth" and "maximum competition" regimes are particularly important to analyze the adaptive strategies of trees to face the environmental constraints in terms of morphology, biomechanics, and ecophysiology.

The stand density regime is tested in all sites. Each site is composed of at least three plots with a different competition level each. Intra-site replication is possible, but inter-site replication is given priority. Thus, a given stand density regimes is repeated under various pedoclimatic conditions, so that relationships can be established between growth, mortality or regeneration on the one hand, and the effects of competition and pedoclimatic conditions on the other hand, and one can even seek for interactions between these two parameters (Trouvé et al. 2014, 2015). Figure 1a illustrates the organization of a site and the differences in the closure/opening of the tree cover according to the stand density regimes (Fig. 1c).

2.3.2 Other factors

Depending on practices and on forest management objectives specific to each system, a second factor can be tested, namely, the mixture rate in mixed stands, and the level of genetic improvement for Maritime pine, which has benefited from an improvement program since 1960 (Vidal 2016). This second factor is cross-tested with the competition level factor (Fig. 1b, d). This experimental scheme allows analyzing the effects of each factor and their potential interactions within a wide range of pedoclimatic conditions.

Other, so-called secondary factors, are tested: in the mixed forest network, the spatial structure of the mixture (in the plantation sites); in the Maritime pine network, reforestation operations (soil preparation, fertilization, and clearing techniques). These factors are tested on some sites, in interaction with the competition level factor. The other forestry factors are checked, and a record of all forestry operations is kept.

2.4 Measurements

2.4.1 Dendrometric variables

The basic principle common to all networks is the permanent identification and the individual monitoring of each tree: all trees over 7.5 cm in diameter in uneven stands, all trees in plantation, and all trees of the main tree layer in even-aged stands issued from natural regeneration. In young even-aged strands issues from natural regeneration, measurements are made on all the trees belonging to the main tree layer of a set of sub-plots of a defined surface to ensure a good representativeness of the stand. As soon as the suitable density is reached, the individual monitoring of all the stems in the main tree layer can start (Table 4). In even-aged stands issues from natural regeneration, the woody understory is measured in

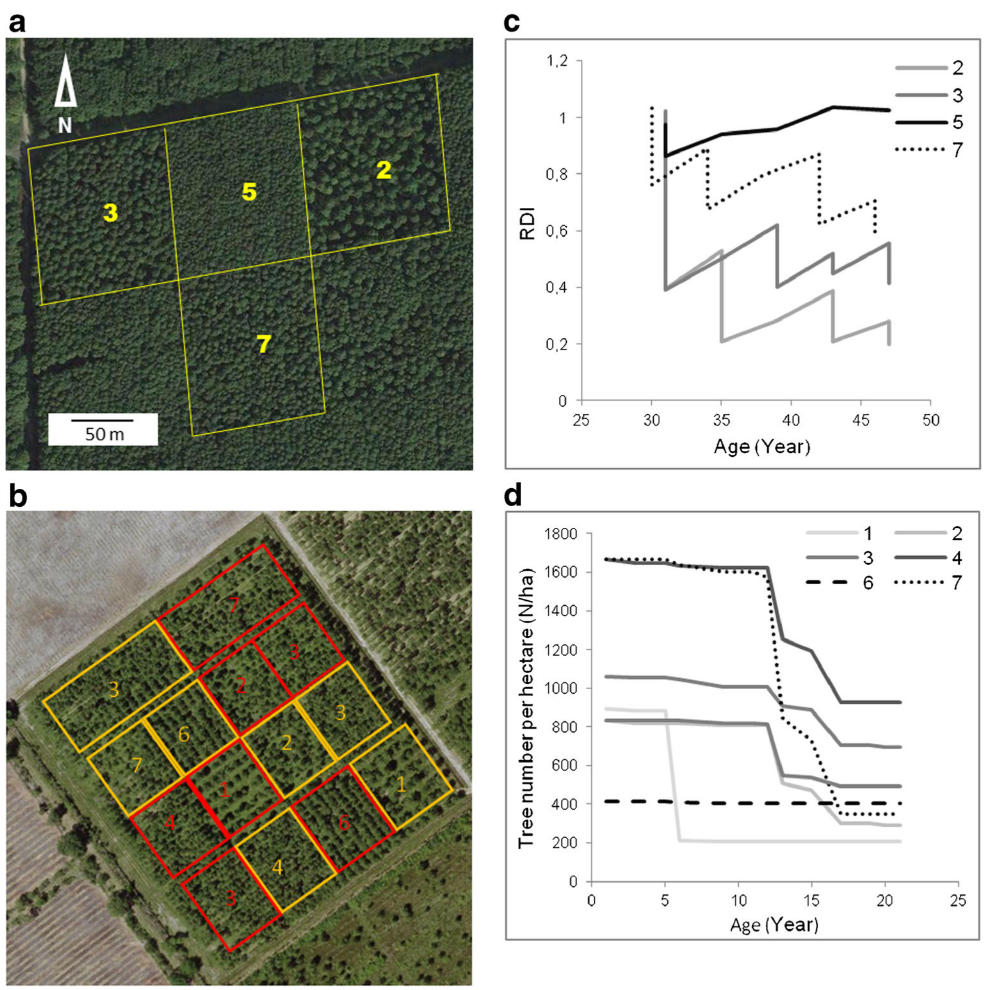


Fig. 1 Two examples of the organization of a GIS Coop site. **a** Case of a site where only the competition level factor (four treatment categories) is tested: Réno-Valdieu, **b** case of a site where two factors are cross-tested, competition level (seven treatment categories) and improved genetic level (two levels showed with the two colors around the plots on the map): Castillonville. For each site, the actual stands trajectories to date are given for all the plots of Réno-Valdieu (**c**) and for plots with one of the two improved varieties tested (Variety Vigor-Form 1) for Castillonville (**d**). Seven treatment categories are defined depending on competition level: 1 open growth, 2 low competition, 3 medium competition, 4 strong competition, 5 maximum competition, 6 increasing competition, and 7 decreasing competition. The plot numbers on the two maps (**a** and **b**) correspond to these competition level categories (**c** and **d**)

Table 4 Description of the measurement protocols

	Sessile and pedunculate oaks	Douglas fir	Maritime pine	Laricio pine	Mixed forest
Monitoring type	All the stems of the main stratum, except if N/ha > 3500 t/ha: systematic sampling (ca. 30 sub-plots of at least 15 stems)	All stems	All stems except if N/ha > 2000 t/ha: systematic sampling (ca. 15 sub-plots)	All stems	- In plantations, all stems - In natural regeneration, all the stems of the main stratum - In uneven-aged stands, all the pre-countable stems (> 7.5 cm diam.)
Measurement frequency*	4 years up to ~ 60 years of age, then 6 years	3 years	3 years	3 years	To be defined soon
Compulsory measurements for all trees	Species Survival C130	Species Survival Ht before 10 years old C130 from 10 years old	Species Survival Ht before 5 years old C130 from 7 years old	Species Survival Ht before 8 years old C130 from 8 years old	Species Survival C130 Ht (for young plantations) Coordinates (for mature stands)
Individual monitoring of forestry treatment	Thinning	Thinning Fill planting Designation Artificial pruning	Fill planting Thinning Artificial pruning	Fill planting Thinning Designation Artificial pruning	Thinning Fill planting (for plantation)
Number of sampled trees	60	25	25	25	To be defined soon
Specific compulsory measurements on sampled trees	Ht Social status Hflb Counting of trunk or sequential green axes	Ht from 10 years old Hflw	Ht from 10 years old Hflb	Ht from 8 years old Hflb Age	Ht
Optional measurements on sampled trees	None	Hflb Stem shape Flexuosity Forking Basal deviation from the vertical axis Basal twist	Stem shape Basal deviation from the vertical axis Hflw Hfdb	Hflw Hfdb Nlw Forking	To be defined soon

This table details the sampling procedures and the measurements performed in each network. Ht is total height, C130 is the circumference 1.30 m above ground, Hfdb is the height of the first dead branch, Hflw is the height of the first living whorl, Hflb is the height of the first living branch, Nlw is the number of living whorl between two defined heights. * The measurement frequency is adapted in case of thinning intervention: in this case, the measurements are performed just before (see Table 2) sub-plots and its development is controlled: trees of understory are cut as soon as their crown reaches the main tree layer.

The measurements are performed outside vegetation period and always just before each thinning. A minimum measurement frequency is also defined for each network (Table 4). In practice, to apply the stand density regimes assigned to the plots, the GIS Coop partners select trees for cutting just after the measurements whenever the stand density index of the plot is above the target density of the associated thinning regime. The thinning operations must be done before the beginning of the next vegetation period. In this way, all plots on an experimental site are measured at the same time and the length of growth periods cannot be longer than the minimum frequency. The growth period length does not vary much that can be an asset when creating the dataset and developing models. But we observe that in exceptional cases, in storm for example, this regularity must be modified always by shortening the frequency of the measurement.

The protocols written for each network (not included in this paper) indicate the measurements to be performed (Table 4), their expected accuracy, their minimum frequency, the materials to be used, and the sampling procedure (for the measurements performed on a subset of trees). In addition, field manuals detail operating modes and software tools have been developed to select the sampled trees for specific measurements (Table 4). All these documents ensure that measurements are performed homogeneously. For some networks, measurements are performed conjointly by the different partners; for other networks, calibration days are organized. Certain events, such as biotic damage (red band needle blight in the Laricio pine network, Perret 2015) and storms (in the Maritime pine network, Jactel 2001) are recorded based on supplementary protocols.

2.4.2 Soil and flora variables

Before 2011, the ecological site characterization of a given site relied on simple criteria: climatic region or even mesoclimate based on data from the closest weather station, floristic composition, site classification, or site index of the previous stand. Since 2011, a common protocol has been set up to collect soil and flora data at all sites at least once during the rotation (Table 5, Annex 2). This protocol is applied 7 years following regeneration at the earliest. The choice of one sole protocol strengthens coherence among networks. All active sites are gradually characterized ecologically. To date, one third of the sites have been described. Characterization provides data not only to estimate soil water content, a key variable for calculating the water balance (Granier et al. 1999), but also to get available data on physical and chemical properties of soils to study the impacts of forestry practices on soil fertility.

3 State of progress of GIS Coop networks and their database

3.1 Networks

Progress in the establishment of the experimental networks is presented in Table 6 and Fig. 2. The Douglas fir and Maritime pine networks are already set up for their most part; the targeted numbers of sites/plots have been reached, and the networks cover most of the production areas of the system. The oaks and Laricio pine networks are still under establishment. As for the mixed forest network, installation started in 2013.

The three coniferous networks integrated sites used by GIS Coop partners before the GIS Coop was created. As a result, stands of various ages were more rapidly available, as well as extensive series of datasets (up to 15 successive measurements and a 45-year long monitoring for the oldest stands). These sites were integrated after checking that they met the requirements of the specifications. The oaks and mixed forest networks do not include old sites. In the oaks network, sites are exclusively installed in relatively young stands (< 40 years old).

Numerous experimental sites were set up in the first years following the creation of the GIS Coop (1994–2000), and new installations have been regularly achieved since 2000 (1–2 per year). After 20 years, this strategy has been effective to achieve a distribution of various stand ages across all sampling years and thus to de-correlate stand age from measurement date (Fig. 3).

Figure 4 shows the distribution of plots according to the competition level in each network. The proportion of plots submitted to extreme "open-growth" or "self-thinning" competition levels is often lower than for the other levels. This stems from the fact that the networks include sites that existed before the GIS Coop was created, where these types of stand density regimes were not tested at the time. This proportion gradually increases with the installation of newer sites.

3.2 Database

As soon as the GIS Coop was created, it included the design and setting-up of a database shared by all networks. The setting-up of this database was possible because the partners agreed to pool their data. The GIS Coop convention and the policy for use of the GIS Coop data/sites delineate the terms of use of the data and of access to the experimental sites. The charter and the request form for data use and/or plot access are available on the GIS Coop website (http://www6.inra.fr/giscoop).

The database is implemented under the database management system (DBMS) PostgreSQL, version 9.2.16 (https://www.postgresql.org/). This DBMS allows for data

Table 5 Measured soil and floristic variables

Observation	Variables
Floristic inventory	Five $40m^2$ subplots by plot
	For each terricolous species:
	Layer (< 2-m height and > 2-m height)
	Braun-Blanquet's abundance/dominance coefficient
Humus description	Five by plot
	Identification of horizons (OLn, OLv, OF, OH)
	Surface covered by each horizon
	Thickness of horizon OH if present and transition to horizon A
	Structure (lumpy or not) of horizon A
	Identification of the humus type according to the soil reference document of Baize and Girard (2008)
Auger boring	Five by plot
	For each horizon:
	Thickness
	Texture (according to modified Jamagne, Baize 1988)
	Presence of coarse elements (> 2 mm)
	Intensity of effervescence in the presence of HCl
	Percentage of hydromorphy traces (reoxidation, reduction, loss of color)
Soil pit	One or two by trial
	For each horizon until 150 cm depth:
	Thickness
	Color (Munsell code, cover, nature)
	Texture (according to modified Jamagne, Baize 1988)
	Structure (aggregate type and size, degree of development)
	Compactness
	Presence of coarse elements > 2 mm (size, abundance, nature, shape, arrangement)
	Living roots (size, abundance, penetration)
	Iron-manganese concretions (abundance, hardness, color, size, shape)
	Identification of the soil type according to the soil reference document of Baize and Girard (2008)
Soil sample	One composite sample by plot, 0–10 cm depth
	Measured variables:
	Water pH and $CaCl_2$ pH (only for samples taken in soil pit)
	Total (if pH > 6) and active (if effervescence in the presence of HCl) limestone
	Organic carbon, total nitrogen
	CEC, H+ and exchangeable elements (cobaltihexamine extraction)
	Phosphorus (Duchaufour's method if pH < 7 or Joret-Hébert's method if pH > 6)
	Granulometry of 5 fractions (only for samples from soil pit)

The description of soil pits was performed according to a similar protocol to that of the RENECOFOR network (RENECOFOR 1995)

structuring and ensures that data are consistent and confidential. Building coherent networks by defining specifications that homogenizes and standardizes protocols made it easier to design a unique database shared by all networks.

The database stores metadata about the sites (name, location, and owner) and the plots (surface, stand density regime…), measurements (year, month, and monitoring type), and the historical record of each plot (all forestry operations are recorded). Each tree is referenced by a number; its species, sometimes its location inside the plot, and the successive dendrometric measurements are recorded. The database has also been storing flora and soil data since 2014. The soil data were modeled to match up with pre-existing French databases about forest soils (Renecofor, Donesol, BioSoil, EcoPlant) (respectively Gégout et al.

Table 6 Description of the networks

	General information						Dendrometric variables				Environmental variables		
	No of sites	No of plots	Year of installation	Age at installation time (years)	Age in 2016 (years)	No of measurements	Dg (cm)	BA (m^2/ha)	Hdom (m)	HB (%)	Mean annual temperature (°C)	Mean summer temperature (°C)	Annual rainfall (mm)
Oaks	22	85	1995–2016	9–39	20–55	1–6	1–24	0.2–55	3–20	8–130	9.7–13.6	16.7–21.2	675–1145
Douglas fir	31	162	1965–2008	2–28	19–68	4–14	3–66	0.5–88	0.5–41	9–140	8.8–12.7	15.8–20.2	765–1586
Laricio pine	14	62	1983–2012	0–45	4–62	2–15	2–47	0.4–70	0.3–25	11–76	9.6–12.8	17.8–21.2	705–1560
Maritime pine	114	861	1944–2016	0–40	1–44	1–13	3–36	0.6–42	3–23	16–76	11.2–14.1	18.5–20.7	726–1295
Mixed forest	4	37	2013–2015	2–94	5–95	1–2	–	–	–	–	9.7–11.1	17–18.5	726–1279

For each variable, the range of values measured in each network is indicated by the minimum and maximum values. BA is stand basal area. HB is Hart-Becking's spacing factor. In the case of planted sites (all the sites of the Douglas fir and Laricio pine, 3/4 of Maritime pine plots), the range of these factors is only given for stands above 5-m height. The temperature and rainfall values are the 1981–2010 norms from the Aurelhy model of Météo France. The dendrometric variables of the mixed forest network are not indicated because the network is quite recent (few sites and a very short monitoring period)

2005; Grolleau et al. 2004; Hiederer et al. 2011; Ulrich 1995) as regards their structure, the nomenclature of the table and field names, and qualitative variable encoding, for the soil databases to interoperate and to make their shared use easier (Augusto and Pousse 2016).

Before uploading data into the base, different semi-automatic procedures are applied to check data quality and coherence (variable type, range of values) among variables (for example, between the circumference at 1.30 m height and total height) and among successive measurements (for example the non-declining values of successive circumferences …). These controls are very time consuming but are essential as a complement to protocols and operating modes to improve quality of data that is particularly required to detect trends in growth that could be attributable to climatic fluctuations or directional change.

By mid-2017, 48 sites, 246 plots, and 76,080 trees were recorded. Altogether, more than 270,000 individual measurements have been recorded. Therefore, each tree has been measured 3.5 times on average. There are also 1377 floristic inventories totaling 510 identified species, 935 auger borings, and 50 soil profiles.

4 Contribution of the GIS Coop to emerging issues in the context of environmental changes

The forestry trial networks were designed to answer forestry scheme modeling questions by recording tree and stand growth. Although the issue of the environmental change, and more specifically of productivity changes (Bontemps et al. 2009, 2010), was already part of the initial questionings, the speed of these changes and the strong uncertainties about their impacts further support the relevance of these kinds of networks and the need for long-term studies.

4.1 Main assets of the GIS Coop

The first main asset is that the GIS Coop has several plots submitted to different competition levels in the same site and then repeated in varied pedoclimatic contexts. Thanks to this experimental design, the networks investigate the "density-climate water balance" scheme beyond the contexts found in the French forest resource, as illustrated for the sessile oak network in Fig. 5. We can more particularly note that (i) the application of the sampling design allows to cover all the range of climatic conditions with a limited site number (22 sites for sessile oak) and (ii) this network includes stands exhibiting a very low competition level (lower than in French forests) throughout the whole range of water balance levels. This large gradient of water conditions is particularly

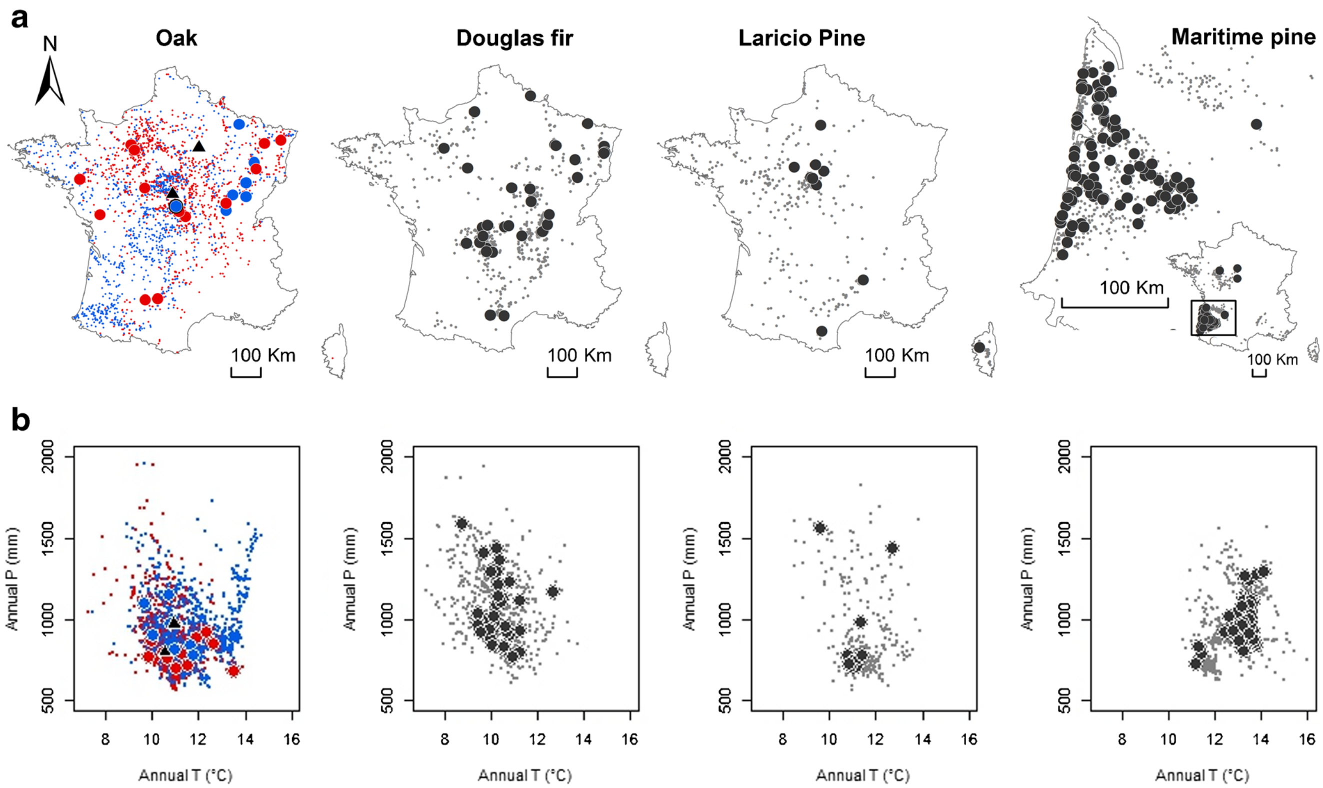
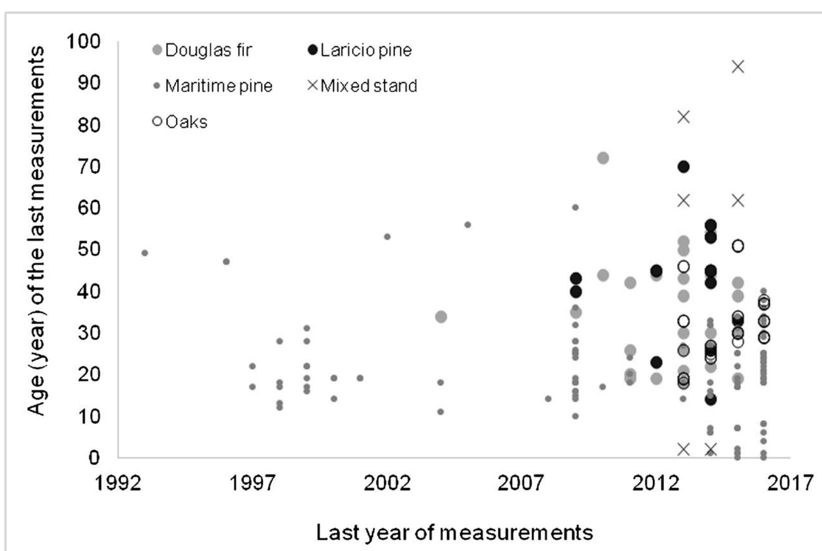


Fig. 2 Geographical (a) and climatic (b) distribution of the sites as related to the distribution area of the forest management systems under study. The distribution of the systems is represented by NFI plots with at least 80% of their basal area occupied by the species and presenting a regular structure. Temperature (Annual T) and rainfall (Annual P) data are the 1981–2010 norms from the Aurelhy model of Météo France. GIS Coop sites are represented by big dots, NFI plots by small dots. Blue dots represent pedunculate oak, red dots sessile oak. Both oak species are tested at two sites (black triangles)

important to define silviculture under more and more constraining water stress according to the different upcoming climate scenarios.

A second asset of the GIS Coop lies in the forestry systems, which illustrate highly contrasted situations as regards environmental changes. Some of these forest management systems appear to be vulnerable. Thus, an important decline of pedunculate oak has been reported from several years (Douzon 2006; Saintonge 1998). It is supposed to be caused by increasing water stress in link with other biotic or abiotic constraints (Bréda et al. 2006; Lévy et al. 1994). Since the early 1990s, Laricio pines have been affected by red band needle blight

Fig. 3 Stand age when the last measurement was performed and year of the last measurement



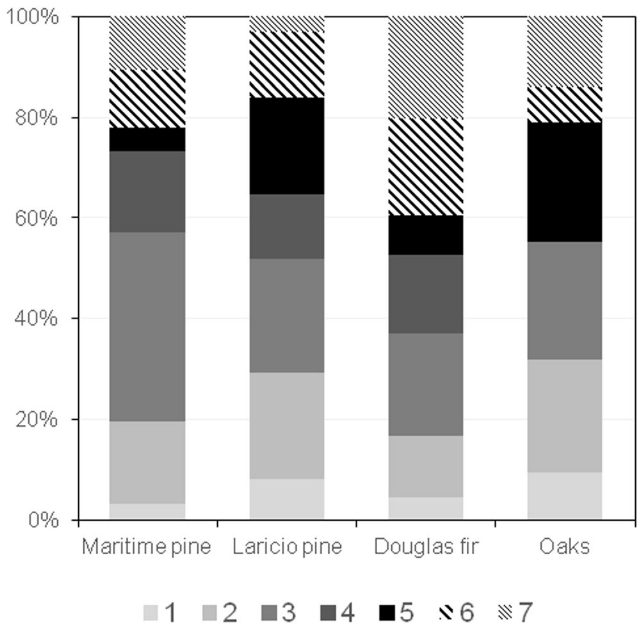


Fig. 4 Number of plots per density treatment type. The densities of the different networks are classified into seven categories: five treatment categories ensure a constant competition level over time, with variable intensity (1 open growth, 2 low competition, 3 medium competition, 4 strong competition, 5 maximum competition), and two treatment categories ensure a variable competition level over time (6 increasing competition and 7 decreasing competition)

(Fabre et al. 2012; Piou et al. 2015), whose recurring outbreaks cause spectacular damage to the sanitary state of the stands. The spread of this disease is thought to be partly related to the climatic changes hypothesized to favor the leaf fungus that causes the disease (Welsh et al. 2014; Woods et al. 2016). These effects are already visible in the GIS Coop network. Over the last 3 years, annual notations of red band needle blight have been performed throughout all the sites of the Laricio pine network within the framework of a multipartner project (DoLar, supported by the Ministry of Agriculture). Substantial production losses are noted in certain sites (Fig. 6). *A contrario*, Maritime pine, which is known to be resistant to summer drought (Kurz-Besson et al. 2016), could be an asset for foresters within the framework of the climate change.

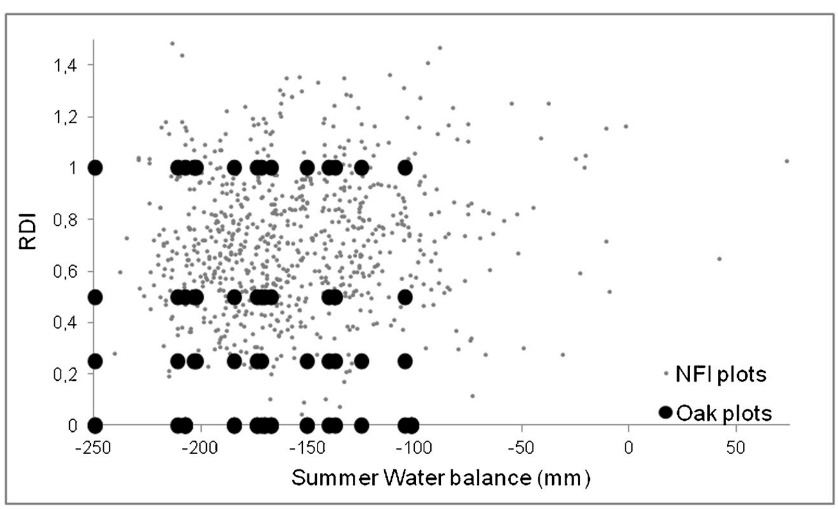
Lastly, the fact that the GIS Coop networks were created recently is also an asset. A great part of the experimental sites were installed after 1990, when mean annual temperatures started to rise in France (Déqué 2007; Planton et al. 2008). Therefore, they are good markers of the effects of the climate change on the dynamics of tree and stand growth, all the more so as the regular installation of new sites causes age to remain independent to date (Fig. 3).

4.2 Ongoing evolutions

Since the inception of GIS Coop, in a context of environmental changes, the needs of forest managers and therefore the growth modeling needs have changed. Three tracks for adapting network design to new requirements have been identified, related to the network sampling scheme and the acquisition of new data.

The first track is related to the geographical expansion of the networks. Site distribution was originally designed to cover the current production area of the forest management systems rather than the distribution area of the systems, so that it did not anticipate their decline in the warmest zones or the possible forthcoming acclimation of sites in cooler zones. Recently installed sites aim to gradually fill this gap targeting more extreme conditions. Two Maritime pine sites have been installed in cooler temperature contexts, in the center and north-west of France. In oaks network, two sites have been installed at the southernmost end of the distribution area of sessile and pedunculate oaks. That allows to extend significantly the summer water balance range covered by the network towards dry climates (Fig. 5; the summer water balance of these two sites are - 250 and - 210 mm).

Fig. 5 Sampling scheme of the oak network within a density—summer (June–August) water balance plan as compared to the resource given by NFI data. The water balance is the difference between rainfall and evapotranspiration, calculated from Thornthwaite's formula using the monthly means from the Aurelhy model of Météo France. The RDI is the Relative Density Index (Reineke 1933) (Annex 1)



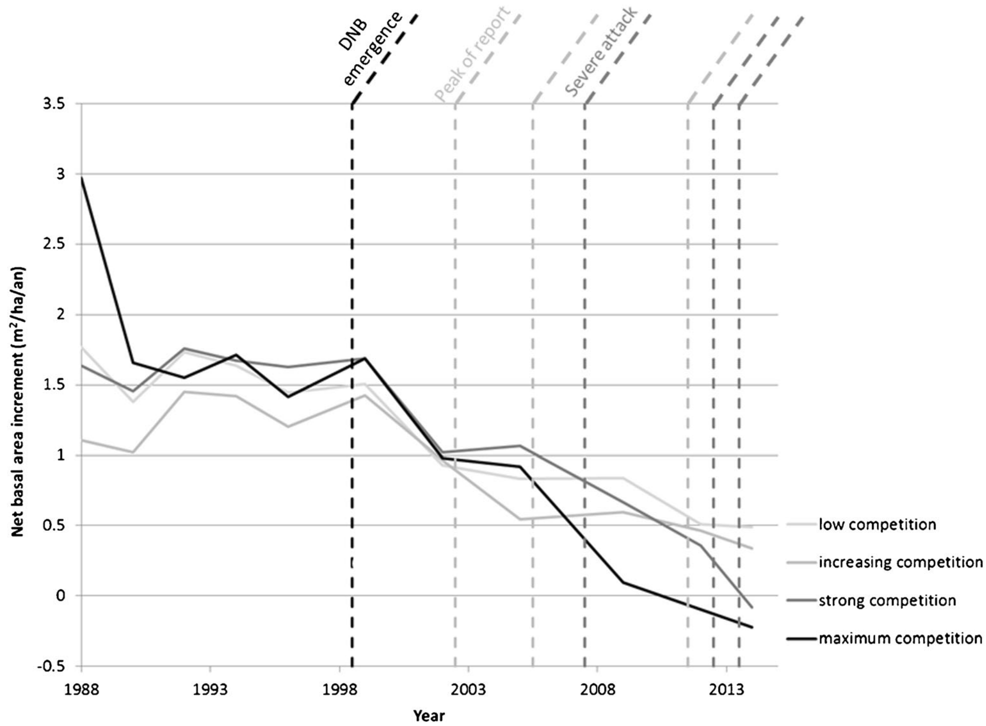


Fig. 6 Evolution of the current net annual basal area increment of four plots with contrasting stand density regimes in the context of the emergence of red band needle blight (DNB) of Laricio pine in the Centre-Val de Loire region (DNB reporting from the Department of Forest Health)

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The second track is related to the site sampling/selection method, which so far had relied on two criteria now considered insufficient, namely, their geographical distribution across the different climatic regions, and their fertility as assessed via a site classification or a site index. But these factors do not elucidate local environmental factors, and they consider the local environment as stable. A work conducted by GIS Coop is ongoing to identify the most important soil and climate drivers for both diameter and height growth in order to define a cogent grid of analytical ecological descriptors and lead to a better network stratification. To that end, a literature review and a data analysis based on the NFI data are currently under way for each species studied by the GIS Coop. This analysis will highlight the species-specific response to pedoclimatic constraints, both in terms of their national distribution (Piedallu et al. 2016) or production (Charru 2012; Lebourgeois et al. 2010; Seynave et al. 2008). In a second step, a diagnostic of the distribution of the present networks along these gradients will be carried out to identify the missing combinations and confounding factors and optimize future installations. As regards with soil data, soil property maps with a spatial resolution of 1 km^2 have been developed for France in the last decades (Piedallu et al. 2011, http://inventaire-forestier.ign.fr/spip.php?rubrique182) and help to identify some areas where to look for new sites. Therefore, field measures can be necessary to confirm the choice of new sites.

Finally, to complete the ecological characterization performed since 2011 and access detailed data about the climate and soil water availability, a few sites are going to be equipped with weather stations and soil humidity probes in 2017. Electronic micro-dendrometers will also be set up to record intra-year circumference growth in link with the climate and soil water availability. This feasibility study will give us information to define conditions for deploying the devices at the scale of all the networks.

5 The GIS Coop experiments are fit for research projects

GIS Coop also undertakes core investigations. The latest study driven by GIS Coop was based on the Douglas fir and oaks networks, and tried to determine how the different silvicultural treatments and climatic conditions modified the growth of trees and stands. Trouvé et al. (2014) showed an effect of the climate (summer water deficit for oak and summer temperatures) on relative growth at the tree and stand scales, with a decrease of individual basal areas that was all the more severe as trees were dominated. Thus, in the case of Douglas fir for example, a 2 °C increase of the mean summer temperature (from 18 to 20 °C) caused a growth reduction of less than 10% among dominant trees, versus nearly 40% among dominated trees. The effect of the summer water deficit has also been demonstrated at a finer scale: at the intra-tree scale, it modifies the allocation of resources between height and circumference growth. By more strongly reducing the height growth of dominated trees, it speeds up social regression within stands (Trouvé et al. 2015).

GIS Coop networks are also a hosting support for exogenous researches. As an example, using GIS Coop oaks network and through a functional approach based on resources (light, water, and minerals), Henneron et al. (2015, 2017b) evaluated the effects of thinning regimes on different diversity guilds: vascular flora and bryophytes, insects, gastropods, earthworms, and collembola. In addition, the effects of thinning on ecosystem functioning were analyzed in terms of carbon and nitrogen balance. The results show that thinning operations do not have unequivocal effects on the different diversity compartments. Certain guilds are favored by severe thinning regimes, while others are favored by low thinning regimes, and a number of relations are not linear, with a bell-shaped curve and an optimum for different thinning levels. Cascade effects have also been identified. Oak litter quality decreases in the plots submitted to the most severe thinning regimes. Confirmatory path analysis evidenced that this effect was related to a change in flora composition linked to increased light in the underwood. This flora causes competition for nutrients, especially nitrogen, with adult oaks. Oaks react by increasing the secondary metabolite concentrations in their leaves; as a result, leaves are decomposed more slowly, and oaks switch from a nitrogen release strategy to a resource conservation strategy (Henneron et al. 2017a).

6 Conclusion

The originality and assets of the GIS Coop lie in that it addresses contrasted forest management systems and tests stand density regimes that include extreme conditions (from self-thinning to open growth), as well as regimes increasing or decreasing competition in various soil and climatic contexts. The standardized experimentation and measurement protocols and the setting-up of a database to structure, secure, and share data are major assets for these experimental devices tested on the long term. The sampling effort has to be substantial and regular to ensure the realization of the prescriptions because experimental sites may suffer various levels of damage (freezing temperatures, storms…) that sometimes require that the trial should be stopped. The withdrawal rate in the Maritime pine network is 39% in 15 years (Meredieu, pers. com.). After collecting data for 20 years, the available data already provide enough information to analyze the effects of forestry practices on tree and stand growth (Trouvé et al. 2014, 2015).

The GIS Coop partners pooled their equipment, their skills, and previous methodological knowledge to build sizeable, coherent networks and thus generate reliable data that represent a large biogeographical domain. This association of the main French stakeholders of forest research and development, which benefits from the support of the ministry in charge of forests, also ensures the sustainability of the experimental sites. But the GIS Coop is also a platform where researchers and forest managers can discuss and debate about trials, protocols, and forestry. When the GIS Coop was created, these discussions led to the formalization of the stand density regimes, and the range of the competition situations to be tested was enlarged. Discussions were also particularly rich within the framework of the definition of the experimental strategy for the mixed forest network (Cordonnier et al. 2012). Recently, these fruitful discussions enable the GIS Coop to modify networks and protocols, with a view to best answering new questions.

Finally, the GIS Coop networks are used as bases for multidisciplinary works. These last years, different projects used GIS Coop networks to address questions that had not been thought of when the GIS Coop was created, such as the impacts of forestry practices on ecosystems and their functioning. Thus, for example, the Imprebio project focused on the impacts of forestry practices in even oak plantations on the biodiversity of different taxonomic compartments (Henneron et al. 2015), the INSENSE project defines indicators of soil sensitivity to the biomass harvest (Augusto and Pousse 2016), or the PiCaSo project studies the impacts of forestry on the carbon stores of forest soils (Cecillon 2016). The GIS Coop is therefore also a potential reservoir for new studies in various domains (ecology, ecophysiology, soil sciences …).

Whatever the ongoing evolutions and the need for new studies, the founding experimental principles and the core measurements originally designed for the networks have to be maintained in a consistent manner, and companion studies that augment the understanding of stand and ecosystem dynamics cannot draw resources away from the basic measurements.

Acknowledgements We would like to thank the GIS Coop presidents, from earliest to latest: Michel Buffet (ENGREF), Christin Ginisty (Irstea), Jean-François Dhôte (INRA), and Alain Bailly (FCBA). We are grateful to the former members of "Cellule Technique" staff who have managed the database and assisted in networks development: Catherine Sindou (INRA), Max Bédéneau (INRA), and Sébastien Daviller (INRA). Finally, we also offer a special thank you to the leading experts who initiated the collaboration: Yves Birot, Jean Bouchon, Pierre Duplat, Philippe Dreyfus, and François Houllier, and to all of the persons who have participated in the data collection (UEFP, INRA, Irstea, ONF, FCBA, CPFA, CNPF-IDF).

Funding The GIS Coop networks benefits from the financial support of the French Ministry of Agriculture and Forest since 1994. As partner of GIS Coop, AgroParisTech (formerly ENGREF), CPFA, IDF, FCBA (formerly Afocel), INRA, Irstea (formerly Cemagref), and ONF support the GIS Coop and have made available more than 175 people since 1994.

The projects below also contributed to GIS Coop networks:

ADAREEX (2017): RMT AFORCE, Ministère en charge des Forêts, France Bois Forêt, Labex ARBRE

CoopEco (2012–2017): Ministère de l'Agriculture, de l'Agroalimentaire et de la Forêt, Office National des Forêts; E16/2012, E31/2012, E22/2015

Dolar (2014–2018): Ministère de l'Agriculture, de l'Agroalimentaire et de la Forêt (DGAL-DSF); 2014-331 et 2015-339

GPMF (2009): Conseil régional d'Aquitaine, Ministère en charge de la forêt

FORBOIS2 (2015–2020): Etat, Conseil régional de Lorraine, FEDER
Fortius (2010–2014): Conseil régional d'Aquitaine (convention n°14007648), DRAAF Aquitaine (ADV14R072000016, AE OSIRIS 150004147365)
Imprebio (2011–2013): Ministère de l'Ecologie, du Développement Durable et de l'Energie, Ministère de l'Agriculture, de l'Agroalimentaire et de la Forêt; 10-MBGD-BGF-3-CVS-081
INSENSE (2014–2016): ADEME, 1360C0088
OBUP (2012): Labex ARBRE
Pinaster (2015–2019): Conseil régional d'Aquitaine (16004034), DRAAF Aquitaine (ADV15R072000012), FEDER (FEDER-FSE-2014-2020 Axe 1)
Sylvogène (2005–2008; convention 06 2 90 6259): Fonds unique interministériel FUI, Conseil régional d'Aquitaine, FEDER
XPSilv (2017–2018): Labex ARBRE

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