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Take five: about the beat and the bar of annual and 5-year periodic national forest inventories

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Abstract

Key message International forest reporting processes and increasing forest disturbances delineate new requirements regarding the information delivered by national forest inventories (NFI), with implications on their sampling strategies. An original comparative review of the sampling designs of 6 pioneer NFI programs being both annual and 5-year periodic evidences a set of common principles used to meet these demands, but also marked implementation differences, and open questions. Bases for a common framework and persisting research needs are highlighted. Developing virtual forest sampling simulation facilities at large scale is a critical challenge.

Context National forest inventories (NFI) rely on diverse sampling strategies. In view of international *forest reporting* processes, these surveys are increasingly adopting a 5-year periodicity (their *bar*). The increased need for delivering updated representative statistics in the context of the environmental crisis is making *annual* forest inventory (their *beat*) a growing standard of the *forest monitoring* approach. To meet both objectives, spatially balanced sampling designs resulting in samples that can be split into yearly systematic subsamples have been devised. They ground the grid-based *interpenetrating panel design* principle that has generated various ingenious designs, however never presented nor reviewed to date.

Aims The purpose of this review was to explore how the *interpenetrating panel design* principle has been implemented by the NFIs that have turned annual. The aims were to describe and frame the diversity of their designs, highlight their common bases and differences, and compare their ability to address new reporting needs. A special emphasis was placed on the graphical representation of these sampling designs. The NFI programs of France, Norway, Poland, Romania, Sweden, and of the USA were considered.

Results The interpenetrating panel design principle is effective in reviewed inventories and is associated with the 5-year moving-window estimator. Original and creative design developments were identified, causing

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Take five is a jazz standard composed in 1959 by Paul Desmond for the David Brubeck quartet. The latter was seeking to develop an album based on odd-time signatures. ***Take five*** is written in a quintuple meter signature. http://en.wikipedia.org/Take_5

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substantial variations in its implementation. They concern panel geometry, unaligned sampling options, sampling unit status, and estimation methods, making no-two inventory designs identical among those reviewed. In these inventories, the notions of annual and cyclic inventory do not substitute for each other, but appear to complement themselves to serve distinct reporting purposes. Also, negative coordination among annual samples is observed, questioning their adequacy for trend monitoring purposes.

Conclusions The review evidences that a core sampling design principle, used to simultaneously operate annual and 5-year periodic forest inventory, has given rise to a diversity of implementation options. While it offers an original benchmark for any survey transition toward an annual frequency, it demonstrates the absence of a standardized framework. Developing simulation facilities for the comparison and optimization of associated designs appears as a critical priority, especially in the context of the EC forest monitoring perspective.

Keywords Forest inventory, Spatial survey, Sampling design, Interpenetrating panel, Annual inventory, Cycle, Periodicity, Estimation, Monitoring

1 Introduction

Surveys dedicated to natural populations require a particular care regarding the distribution of their sampling units across space. Their spatial balance, defined as a regularity of the distance among units (Stevens and Olsen 2004), provides greater statistical efficiency (Christianson and Kaufman 2016). It is mostly ensured by using regular spatial grids (e.g., Olsen et al. 1999) that partition the territory under consideration in a way that spatially *systematic* samples can be drawn (Bouriaud et al. 2023). This solution is widespread in the field of forest inventory (Tomppo et al. 2010; Vidal et al. 2016).

Forests can change rapidly over time and require regular reassessment. Time is therefore a fundamental structural aspect of the design of national forest inventory (NFI) surveys. Accordingly, most NFIs across the world have been deployed on the bases of a pre-defined periodic reassessment—also termed *cycle*—of typically 10 years along the twentieth century (Tomppo et al. 2010). International forest reporting processes, including the UN/FAO Forest Resource Assessment (FRA) after the WWII, and more recently European forest reporting (State of Europe's forests of the MCPFE/Forest Europe protocol since 1990) have yet enforced a typical 5-year reporting periodicity, calling for targeting this shorter time step in forest statistics.

Over recent decades, forests in Europe have also shown dramatic progression in their areal extension and in their growing stock (Bontemps 2021), or changes in tree species proportions (Audinot et al. 2020), all resulting from the forest transitions (Meyfroidt & Lambin 2011). Forests are also being increasingly subjected to major disturbances, as a likely outcome of ongoing climate change (Cornwall 2016). Major storms of the early twenty-first century and their consequences across European forests have first stressed the limits of delayed periodic surveys (e.g., *Lothar* 1999 storm in France, and its consequences on the French NFI design; Vidal et al. 2005). Other emerging disturbances (heatweaves, Ciais et al. 2005; insect-driven diebacks like bark beetle outspread in Europe, Hlásny et al. 2021) figure out emerging disturbance regimes (Seidl et al. 2011), and recall the urgency of a rapid delivery of representative statistics on forests, ideally annual (Gillespie 1999), in addition to consolidated statistics over a given 5-year period. Given the fundamental uncertainty of their spatial occurrence, systematic sampling remains a straight way to quantify their impact. In this context, a new horizon for NFI programs lies in the double capacity of assessing forests over a short periodic—typically 5-year—time range, and at a more reactive and yearly time step, whereby precision, but not representativeness, would be traded against reactivity. These two temporal constraints can be viewed as defining the *bar* and the *beat* of the associated sampling designs.

For the sake of practical survey management, the sampling effort should be distributed evenly over years of a typical cycle (De Gruijter et al. 2006). In forest inventory, this has however resulted in classical flaws, with either a rotation of spatial units inventoried all along a cycle, yielding space–time imbalances and the impossibility of a dated estimation embracing all country's forests (e.g., Vidal et al. 2005 in France), or alternatively to a concentration of inventory operations on restricted time periods with long interruptions, requesting resort to temporary and untrained staff (Tomppo et al. 2010). To address the aforementioned needs, the idea has therefore come forth that a yearly fraction of the sampling grid used during a cycle should also be spatially systematic, hereby paving the way for delivering representative annual forest statistics (Breidenbach et al. 2020). While the Swedish inventory has played an obvious pioneer role in this respect (as of 1953, Fridman et al. 2014), the idea has been emphasized again at the turn of the recent century in the USA (FIA, van Deusen 1999) and across Europe, a consequence of international NFI networking activities favored by EU COST actions (Tomppo et al. 2010). The notion is embodied in the concept of fractionation of a systematic sample into systematic *interpenetrating panels* remeasured periodically. It builds on the seminal work by Mahalanobis (1946; van Deusen 1997) that used a two-panel fractionation concept for a control of sample quality across space. According to Fridman (2014), *the so-called interpenetrating panels have almost become an international standard toward which NFIs in other countries aim*.

Forest inventories that base data collection on systematic annual samples are termed *annual inventories*. They should be distinguished from *continuous forest inventories* that are based on permanent sampling units occasionally remeasured (de Vries 1986), either exclusively, or as a mix with temporary plots intended to capture changes in the population (sampling with partial replacement, SPR, Ware & Cunia 1962; Houllier 1985). A few inventories are therefore both annual and continuous. In terms of sampling design, this translates into a spatially systematic grid-based design covered over a period (their *bar*), and of which each annual sampling fraction, or panel, is even also spatially systematic (their *beat*).

In a recent article, Bouriaud et al. (2023) provided the theoretical algebraic bases for square grid fractionation into interpenetrating systematic sub-grids. The 5-year periodicity, as adopted by the French NFI, happens to be one solution to this problem, as well as the 9-year one (implemented in the Swiss national forest inventory, Brändli et al. 2020), and multiple-of-two solutions (2, 4, and 8 years, typical periodicities found across US environmental surveys, Olsen et al. 1999). The geometric solution to the 5-year periodicity has been identified at several independent occasions (SAFIS US pilot forest inventory; Reams and van Deusen 1999; Polish forest inventory; Michalak and Zajączkowski 2010). However, grid-based fractionated sampling is not used by all inventories. Other designs and varied fractionation options softening the principle of perfect spatial systematicity have also been identified across NFIs.

These preliminary explorations suggested the interest of a review dedicated to the sampling design aspects of the NFIs that accommodate for these temporal properties. Surprisingly, sampling designs have been let aside of previous international synthesis and harmonization efforts in forest inventory (an earlier synthesis, not covering panelized inventories, is provided by Lecomte and Rondeux 1991). Adding to this interest, political incentives toward a pan-European forest monitoring (Bontemps et al. 2022) arising from the new European Forest Strategy (European Commission 2021) question the capacity of NFI methods to meet the goals of changing their *bar* (the reporting tempo) while ensuring a fundamental annual *beat* (associated to the spatial coverage). Third, the approach is meaningful for those inventories still having a periodicity longer than 5 years, or wishing to benefit from an international review of practice when transitioning toward an annual inventory.

The objectives of this review were as follows: (i) to provide a systematic description of the NFI designs based on the principle of an annual interpenetrating paneling of a systematic base design into 5 fractions, with a particular emphasis on their graphical representations, (ii) to identify common core principles but also individual original options adopted to handle the issue, including the aspect of temporal statistical inference, (iii) to synthetize and discuss these approaches, and highlight their main features, their limits, and research questions that could guide future progress.

2 Sampling design and temporal inference practices in periodic and annual forest inventory surveys

Six NFI surveys reviewed met the criteria of being annual and 5-year periodic and included those of France, Norway, Poland, Romania, Sweden, and the USA. While not reviewed in depth, three NFIs with alternative periodicities were also discussed, including the Swiss NFI (9 years) and the Belgian NFI (10 years). These were complemented by the Finnish NFI (5 years) that shares many attributes with the Swedish NFI, but whose sampling design is already accurately documented in Tomppo and Tuomainen (2010) and Tomppo et al. (2011). To the best of our knowledge, this forms a comprehensive list of existing annual forest inventory programs. The main features of the forest inventory designs under review are summarized in a systematic way in Table 1and Table 2.

2.1 The French NFI design and the square-grid fractionation problem

The French NFI design was renewed in 2005 with the objective to deliver annual estimations of forest parameters, after the severe windstorm Lothar of 1999 and the need to rapidly assess the resulting damages. The vision was inspired by the American NFI (FIA; Vidal et al. 2005) and is relying on the principle of interpenetrating annual and spatially systematic sampling panels. Each of the resulting panel subsamples supports yearly forest estimates, in addition to average estimations computed over several samples. A description of the design is provided in Hervé (2016).

A square grid-based approach was adopted to define a sampling frame (grid cells) from which forest inventory

Table 1 Synoptic comparison of the 6 NFI surveys under review according to major sampling and inference criteria. [a]The American NFI is termed Forest Inventory and Analysis, [b]KMD: knight's move design, [c]USS: Unaligned systematic sampling, [d]SU: sampling unit

NFI survey	Geometric design	Periodicity	Paneling geometry	USS condition[c]	Distance between panel SU[d]	SU status (field plot) (+cluster SU number and between-Su distance)	Estimation framework	Reference
French NFI	Square grid	5 years	Squared sub-grids (KMD[b]), 5 panels	Yes, su location randomization within cells	2√5 km (4.5 km)	Semi-permanent su (5 years)	Moving-average estimator (5 years)	Vidal et al. 2005 Bouriaud et al. 2023
Polish NFI	Square grid	5 years	Squared sub-grids (KMD), 5 panels	No	4√5 km (9 km)	Permanent cluster (5 su, 400 m)	Moving-average estimator (5 years)	Michalak & Zajączkowski (2010) Talarczyk (2014)
US FIA[a]	Hexagonal grid	5 years (+variations)	Parallelogram-shaped sub-grids (KMD), two directions (unaligned)	Yes, su location randomization within cells	17/11.3 km in the two panel directions	Permanent cluster (4 su, 36.5 m)	Multiple estimators including the moving-average estimator (5-years) and the time-independent estimator	Bechtold & Patterson (2005) Westfall et al (2022)
Norwegian NFI	Square grid	5 years	Latin squares, 5 panels	Yes, randomization of panel cell location	9/37 km between cluster centers (min, max)	Permanent cluster (9 su,3 km)	Moving-average estimator (5 years) Single-panel estimation at a country level	Breidenbach et al. (2020)
Swedish NFI	Strips and parallelogram-shaped grid	5 years	Parallel bands of parallelogram-shaped cells (two directions, unaligned)	No for permanent su, 2 positions for temporary su	4√5/√5 km (9/2.2 km) in the two permanent panel directions variable for temporary strips	Temporary and permanent clusters (8 to 12 su, 200 to 600 m depending on regions)	Moving-average estimator, weighting of estimations from permanent and temporary samples	Ranneby et al. 1987 Fridman et al. 2014
Romanian NFI	Rhomboid grid	5 years	Parallelogram-shaped sub-grids (one single direction) 4 panels	No	4√5 km (9 km) 2√13 km (7.2 km) in the two panel directions	Permanent cluster (4 su, 250 m)	Full cycle (time independent) Single panel estimations	Bouriaud et al. 2020

Table 2 Sampling strategies used among NFIs based on systematic annual panels with respect to spatial alignment. Unalignment can be sought for at two different stages: (i) at a wide spatial scale in the spatial grid paneling design and (ii) at a local spatial scale in the sampling unit location strategy within grid cells. The deployment of plot clusters enabling the capture of local variability can also be seen as a third complementary degree in this approach. The table splits the reviewed NFIs according to the use of none, one, or both unalignment options. For the sake of comparison, some inventories were added to the review including the 9-year periodic Swiss NFI (Brändli et al. 2020; Vidal et al. 2016), the 10-year periodic Belgian NFI (Rondeux et Lecomte 2010; Tomppo et al 2010), and the 5-year periodic Finnish NFI (Tomppo and Tuomainen 2010). [a]PP = permanent plot, TP = temporary plot, PPC = permanent plot cluster, TPP = temporary plot cluster. [b]Depending on the NFI region, parallelograms of PPC can also be slightly unaligned (Fridman, pers. comm.)

Spatial sampling strategy	Grid-level strategy		Field sampling unit location strategy		Field unit status[a]
	Aligned	***Unaligned***	***Aligned***	***Unaligned***	
Switzerland	Square grid		Fixed position (grid nodes)		PP
Romania	Aligned parallelogram-shaped grid		Fixed position (grid nodes)		PPC
Poland	Square grid		Fixed position (within cell)		PPC
Belgium	Rectangular grid		Fixed position (at nodes)		PPC
France	Square grid			Random position within cell	TP
Norway		Latin square from a grid	Fixed position (within cell)		PPC
Sweden	Aligned parallelogram-shaped grid[b]	Parallelogram shaped-grid of alternate directions	Fixed position within cell	Alternate horizontal position in the cells	PPC TPC
Finland	Square grid	Unaligned square grid	Fixed position	Alternate horizontal/vertical position	PP TC
USA		Parallelogram-shaped grid of alternate directions		Random position	PPC

plots could be sampled. An originality lies in the double objective: (i) that the annual panels should each also form square grids to respect a principle of even spatial distribution of sampling units across the territory, (ii) that the inventory periodicity should be 5 years, according to a standard that has been spreading across forest inventories (Tomppo et al. 2010), thus implying a number of five interpenetrating panels. The base grid side size is 1 km.

In their contribution, Bouriaud et al. (2023) recently showed that the problem of fractionating a spatial square-grid into interpenetrating square sub-grids admits several solutions. With 10 as an upper bound, these solutions include the trivial ones obtained by recursive half-grid fractionation (2, 4, and 8), but also less obvious ones, namely 5 and 9. That 5 appeared to be a solution of this fractionation problem is fortunate in view of international forest reporting processes, and it was adopted by the French NFI. This solution is illustrated in Fig. 1a. It is also known as a *knight's move* deterministic Latin square design (Owens 1987). Of note, each sampling unit (field plot) is selected randomly within each grid cell to meet some form of unaligned sampling (Quenouille 1949) that avoids linear or periodic artifacts (de Gruijter et al. 2006). All sampling units of this survey are temporary, allowing for a full renewal of forest samples across years (de Gruijter et al. 2006). However, the need to better track for wood fluxes led to decide a permanent systematic and 5-year re-inventory of initial sampling units in 2010, embodied in the notion of semi-permanent plots (re-assessed only once). This original design has no equivalent across NFI designs.

Van Deusen (1999) has warned about the rigidity of such a design, articulated across years, and the potential difficulties arising from non-completion of yearly panels, as it may result from, e.g., budget or technical constraints. This call for reactive flexibility has also been pleaded for in survey sampling frameworks (de Gruijter et al. 2006, chapter 3). Among the theoretical suggestions for increasing this design's flexibility, an extra-paneling option has been proposed (van Deusen 1999), whereby the sampling effort could be reduced by a suitable factor, depending on the level of extra-paneling. Profit from this approach is readily made possible in the design of the French forest survey, as the 5-year paneling can be implemented on a half-fractionation of the initial grid (Fig. 1b), and as many times as needed on a power-of-two scale of the sampling size, without sacrificing design systematicity (Bouriaud et al. 2023). This notion of level is implemented in the French NFI, and forest field plots

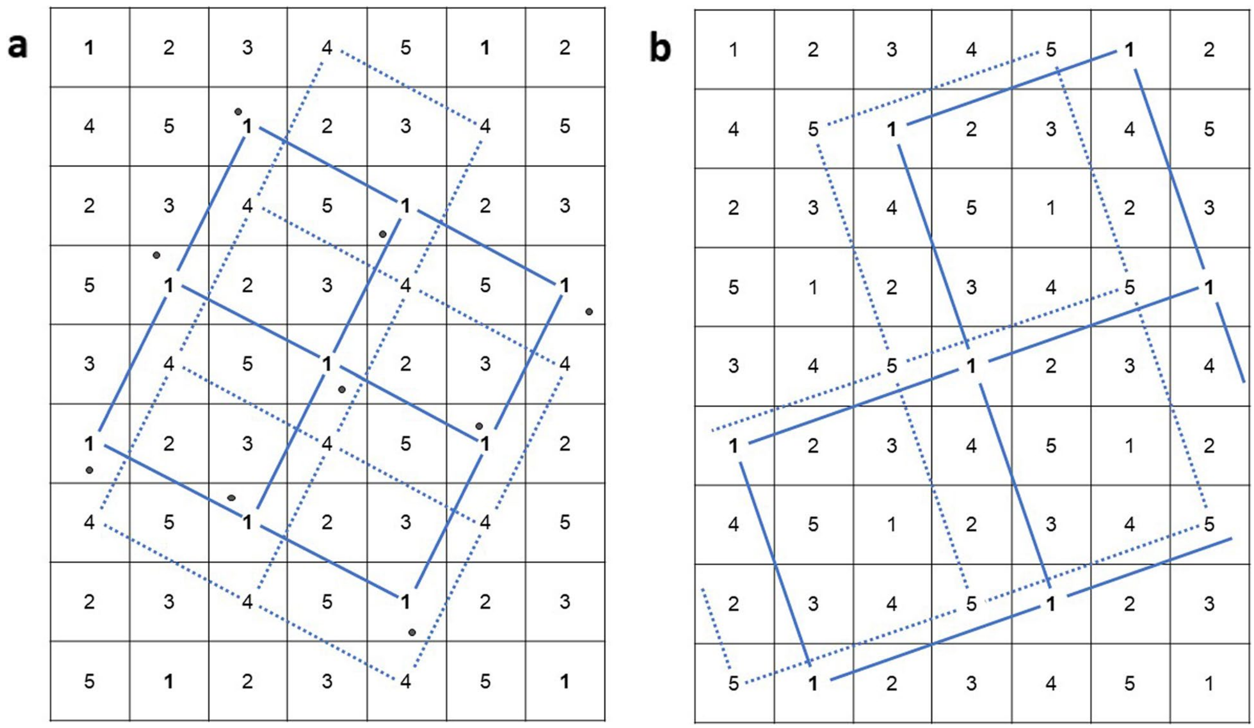

Fig. 1 Spatial grid design of the French annual forest inventory survey as adopted since 2005. The design is based on the interpenetrating panel approach. Each number corresponds to one panel/year one grid cell is assigned to, for a final periodicity of 5 years. The cells themselves define a square sub-grid, ensuring a yearly systematic spatial cover of the forest population (illustrated for years 1 and 4 in **a**, and 1 and 5 in **b**). For panel 1, the dots illustrate the within-cell random sampling of unit locations. **a:** Grid scheme for a base sampling grid. **b:** Alleviation of the sampling effort by a factor of 2 maintaining spatial systematicity (notion of *level*), used for the sampling of different vegetation categories (redrawn and adapted from Bouriaud et al. 2023)

measured in one annual panel have a distance of $\sqrt{2}0$ km from one another.

For the sake of statistical inference, the 5-year moving average estimator, i.e., the average of annual means or totals (van Deusen 2002) was adopted. In practice, the NFI system also affords point estimation in time that includes any combination of successive years (the *time-indifferent* estimator of the US FIA; Roesch and Reams 1999; Bechtold and Patterson 2005). Therefore, periodicity appears to be a property of the sampling design, but it does not lead to any form of cyclicity in the statistics delivered (however see Discussion).

The design properties of this NFI survey and those that follow are summarized in Table 1.

2.2 The Polish NFI—an incidentally comparable design

A new NFI design was decided in Poland in 2004, which is described extensively in Michalak and Zajączkowski (2010) and Talarczyk (2014). The design corresponds to a spatially systematic sample, distributed across a square grid of cells of 4-km side size. This grid is subdivided in repeated blocks of 5 cells, fixed in both their geometry and orientation (Fig. 2a). Each cell of a block is assigned to one yearly sampling panel ranging from 1 to 5 with one corresponding sampling unit, with an attribution of cells to panels set fixed across space. In contrast to the French NFI, sampling units have a strict permanent status and their position in the cells are not randomized. Also, they are organized in clusters of 5 field plots. Therefore, measurements are performed on one cluster per block every year, ensuring an equal 20%-fraction of clusters being measured annually.

Since the block patterns are repeated throughout the territory, the cells and sampling units associated to one yearly survey appear to be distributed systematically across space, on square sub-grids of $4\sqrt{5}$ km side size. These annual grids happen to be interpenetrating, showing an exact incidental coincidence with the design adopted in the French NFI (Bouriaud et al. 2023, Fig. 2b). The design thus belongs to systematic aligned sampling, the position of sampling clusters being identical in each grid cell.

This inventory has been termed *cyclic* and *5-year periodic* in Michalak and Zajączkowski (2010), with the first cycle corresponding to 2005–2009. However, the more recent publication of Talarczyk (2014) indicates that this

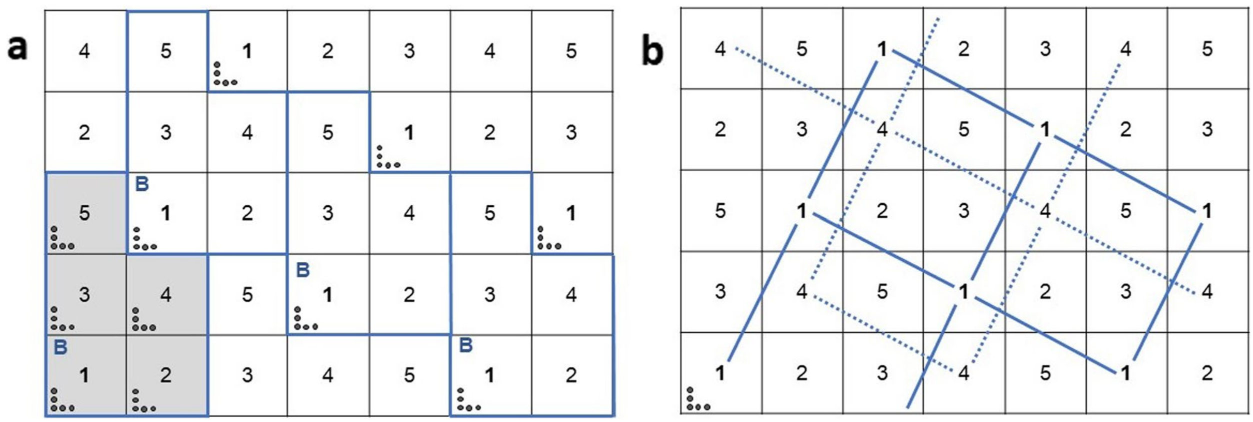

Fig. 2 Spatial design of the annual Polish national forest inventory survey as adopted since 2004. The design is based on the interpenetrating panel approach, using 5-squared-cell blocks (B, highlighted in gray) of fixed shape and orientation (**a**). Each number within one block corresponds to one panel/year one grid cell is assigned to, for a final periodicity of 5 years. The cells of one panel therefore happen to define a square sub-grid (**b**), ensuring a yearly systematic spatial cover of the forest population (illustrated for years 1 and 4 in **b**) and therefore comparable to the French forest survey design (Fig. 1). Sampling units (field plots) are organized in 5-plot clusters of L-shape, occupying a fixed spatial position in each grid cell (redrawn and adapted from Michalak and Zajączkowski 2010 for 2a, and from Bouriaud et al. 2023 for 2b)

survey is also designed for *continuous inventory*, able to deliver updated annual forest statistics also using a 5-year moving window approach, since completion of this first cycle. While it is stressed that *any dataset from five consecutive years has full statistical value, and the design continuously provides up-to-date information each year* (Talarczyk 2014), the delivery of annual statistics solely based on one single yearly sample is however not mentioned in these reference texts.

2.3 The US NFI (FIA)—a panel design resulting from several compromises

The US *forest inventory and analysis* (FIA) survey was initiated in the 1930s, performed at a state level, with a periodicity ranging from 6 to 15 years, and a mode of 10 years (van Deusen 1997). Issues related to the timeliness of forest statistic delivery, to greater national consistency, and to integration of monitoring systems (*Forest Health Monitoring* program, FHM and the FIA), were embodied in the *Farm Bill* act of 1998 (van Deusen 2002) and led to a full renewal of the sampling design in the 1990s (van Deusen 1999). Initial prescriptions included the adoption of a 5-year periodicity and led to implement an interpenetrating panel design with a 20% fraction measured annually, with reference to the seminal work of Mahalanobis (1946), and explicit concern for informing forest disturbances (Gillespie 1999). Of note, a competing pilot design was also explored to promote more frequent statistics, namely the *disturbance-based* design, intended to give greater inclusion probabilities to sampling units found in disturbed areas (Hansen et al. 1998). With both increasing environment-driven forest disturbances (Seidl et al. 2011), and remote sensing facilities, such design strategy has seemingly been remaining under-considered over recent decades. Also, a pilot study of a 5-year periodic interpenetrating panel design tested in Southern states (SAFIS, Reams and van Deusen 1999, see their Fig. 1) adopted the exact same grid/panel scheme as the French and Polish inventories, again stressing the relevance of this option.

An objective of this reform was also to merge the FIA program with the *Forest health monitoring* (FHM) program, whose design was based on a triangular grid and, also, the interpenetrating panel concept, making it possible to accommodate for periodicities of 3, 4, 7, 9, and 11 years (with an actual periodicity of 4 years, Olsen et al. 1999). Therefore, a hexagonal tessellation (cells surrounding a triangular base cell) was adopted that enabled a 5-year periodicity, provided that a parallelogram-shaped tessellation of each panel was adopted (Bechtold and Patterson 2005, Fig. 3). As a difference to previous square-grid designs, the average distance across sampling units of one panel are not identical in the two main sampling directions, indicating a direction-driven variation in the sampling intensity, compensated for after a full cycle. With base hexagons of an area of 5937 acres, the hexagon side size is around 2830 m, implying average distances of around 17/11.3 km between the cells of a given panel in the two directions of the parallelograms.

The sampling units of the FIA design are permanent and are arranged as clusters of 4 field plots (Bechtold and Patterson 2005), a design option comparable to that of the Polish inventory. These plot clusters are however positioned at a random location within each hexagon

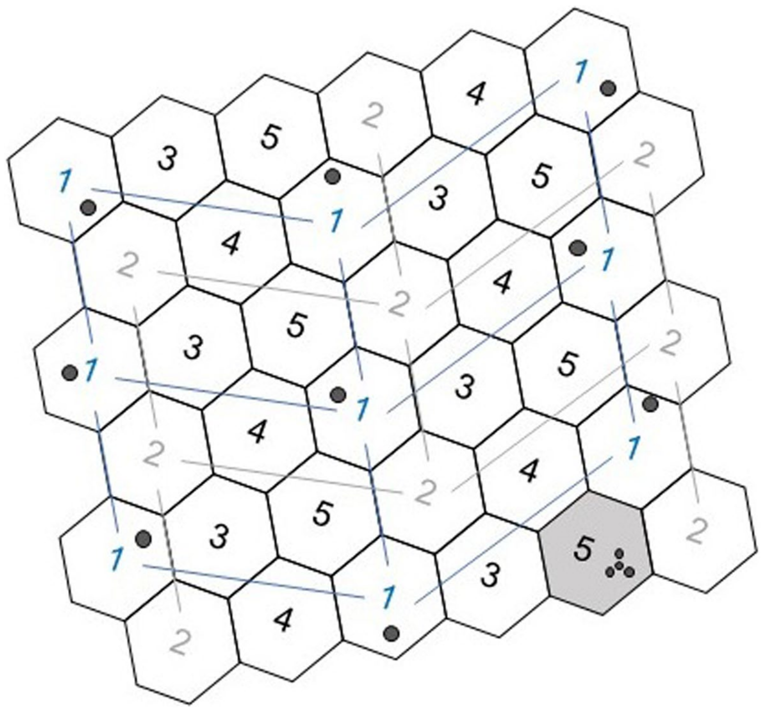

Fig. 3 Spatial design of the US FIA annual forest inventory survey as adopted after the Farm Bill of 1998. The basic design is based on the interpenetrating panel approach applied to a basic hexagonal-grid tessellation of the territory. Each number assigns one grid cell to one yearly panel, the spatial design of which being a parallelogram-shaped grid (represented for panels 1 and 2). Within each cell, the location of the sampling units—a permanent cluster of 4 field plots as illustrated in the gray-filled cell—is drawn at random to permit unaligned systematic sampling (redrawn and adapted from Bechtold and Patterson 2005)

(Tomppo et al. 2010; Tinkham et al. 2018) to meet the condition of unaligned systematic sampling, as found in the French inventory.

Regarding inference, no core method was decided (Bechtold and Patterson 2005; Westfall et al 2022), with recurrent hesitations/tests between/of different estimators often reported in the literature. Inference was further made more complicated by panel incompletion issues (the so-called *panel creep*, van Deusen 2002), causing strongly variable re-measurement periods across panels and the need for corrected estimators (Roesch 2018). This inference aspect has been a matter of recurrent research to date (e.g., Johnson et al. 2003; Roesch & van Deusen 2013; Roesch 2018; Hou et al. 2021). However, some estimators have been readily implemented in the FIA, including the *time-indifferent* estimator for forest status inference (one panel sample or aggregation of several panels), the *5-year moving average* estimator as a way to address a regular update of the statistics to comply with the Farm Bill, and a *mixed-estimator* approach including a data updating component to accommodate for variable time steps in panel revisit (van Deusen 2002; Patterson & Reams 2005; Roesch 2018), depending on the inferential purpose. In this inventory program as well, the yearly sampling effort made it inaccurate to base the estimation process on a single panel in practice.

2.4 The Norwegian NFI and the Latin square approach

The current design of the Norwegian NFI survey has been implemented in the seventh inventory of 1994 and is described in Tomter et al. (2010) and Breidenbach et al. (2020). While the Norwegian NFI is presented as a periodic inventory with a 5-year *cycle* (Tomter et al. 2010), it also belongs to annual inventories, with one fifth of the territory being surveyed each year, also according to an interpenetrating panel design (Breidenbach et al. 2020). The explicit reason behind the notion of *cycle* lies in the objective to maintain the sampling design and data collection protocols mainly constant over a 5-year period (e.g., 2005–2009, 2010–2014). Nevertheless, a 5-year moving-average estimation process is also implemented, for both the purposes of LULUCF reporting (Tomter et al. 2010) and the requirements of the annual reporting of *Statistics Norway* (Breidenbach et al. 2020). This aspect well emphasizes the balance to be maintained between the innovation facility as permitted by an annual inventory, and the need to maintain constant standards and coherent statistics.

Of note, and while not being initiated for a 5-year period, the concept of interpenetrating annual samples is much older in Norway and reflects the pioneering tradition of Nordic countries in forest inventory (see the Swedish inventory below). As of the 4th NFI cycle of 1964–1976, 1/12th of inventory plots, distributed over the whole country, were inventoried each year to provide fast estimates at the country level (Breidenbach 2020).

The sampling design relies on a square-grid tessellation of 9 km side size, organized in squared blocks of 5×5 cells (45×45 km), defining a Latin square used to fractionate the sampling effort evenly into 5 annual fractions (Fig. 4a, see also van Deusen 1999). The same Latin square is repeated indefinitely over the territory (in the same way as the pattern of year assignment was constant among blocks in the Polish NFI) and was defined under the constraint that no two neighbor cells of one given yearly panel are found adjacent within and across blocks (Fig. 4b, Breidenbach et al. 2020). An incidental outcome is the spatial distribution of the first-year panel according to a square grid (the knight's move of the French and Polish NFIs). Further panels (years 2–5) do not show the same regularity.

The sampling units are formed by clusters of 9 permanent plots in each cell, positioned on a predefined finer grid of 3 km side size (Fig. 4a, 15×15 = 225 grid nodes are encompassed in a Latin square for the positioning of permanent plots). A 3×9 km grid can also be used in low-productive regions (Breidenbach et al. 2020). The logic (blocks, permanent plot clusters, fixed position) is therefore very close to that of the Polish NFI survey. At less regular occasions (15 years), these clusters are also complemented with 3–11 temporary plots for increasing the precision of forest estimates at a county level, hereby implementing a mixing strategy of permanent and temporary sampling units.

Owing to the Latin square repetition, the design borrows to the ideas of both unaligned systematic sampling and cluster sampling (van Deusen 1999). This highlights the fact that unaligned sampling can be achieved in different ways: either through the random location of sampling units within grid cells, or through Latin square/block randomization. The design does ensure the interpenetration of annual panels and systematic coverage over space, and may behave better than the systematic design when spatial autocorrelation or periodic spatial patterns exist in the population (Munholland and Borkowski 1996).

2.5 The Swedish NFI—the legacies of pioneer implementation of interpenetrating panel design

The Swedish NFI has been pioneering the implementation of interpenetrating annual panels, regularly spread across space, and several variations have therefore been introduced over time (see Fridman et al. 2014 for a detailed overview). In 1953, this inventory moved from a 10-year cyclic inventory implemented at county level, to an annual approach whereby each sample was systematically spread across the Swedish territory and represented one 10th of the sampling effort every year. This shift is therefore similar with that observed in forest inventory surveys of the USA and France. Also, by comparison to the French NFI survey, samples were exclusively composed of temporary sampling unit clusters at that time.

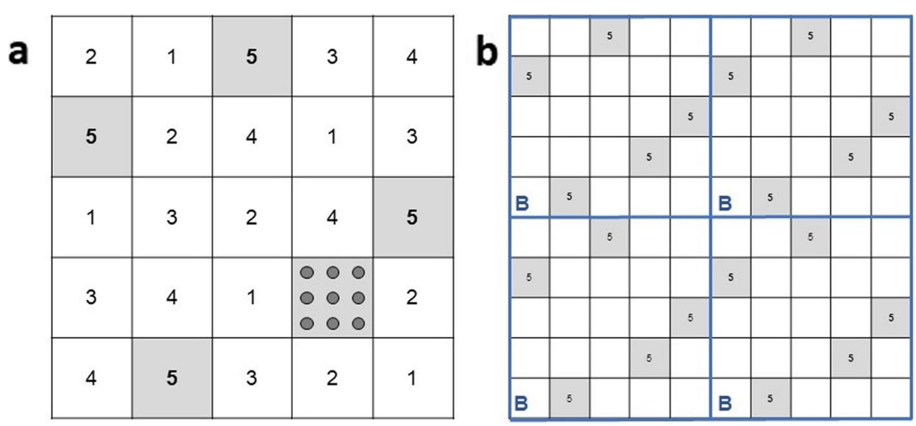

Fig. 4 Spatial design of the Norwegian annual forest inventory survey as implemented since 1994. The spatial design is based on a square grid, tessellated in blocks of 5×5 cells. Each block is formed by a Latin square (**4a**) for the assignation of each grid cell to a yearly panel, with similarity to the Polish forest inventory survey. The same Latin square is repeated indefinitely over the territory (**4b**) and allows interpenetration of the yearly panels, in a way that generates a regular coverage of the territory each year (example with panel 5 in gray), borrowing to unaligned systematic sampling (note: an incidental exception is formed by panel 1 which distribution is spatially systematic (knight's move pattern), in a way thus similar with the French and Polish inventories). (Redrawn and extended from Breidenbach et al. 2020)

The statistical accuracy of the estimations was found sufficient to implement a 5-year moving-window average for official statistics, with annual delivery. Also, as found in the Norwegian inventory, special reports were delivered based on a 5-year cycle (Fridman et al. 2014).

Later achievements included a shift to an annual intensity of 1/5th of the sampling effort every year in 1973, the introduction of permanent sampling unit clusters in 1983 for a better estimation of forest change, with an equal number of temporary and permanent clusters, and the consolidation of a 5-year periodicity for permanent cluster re-measurement as of 2003 (see Table 1 in Fridman et al. 2014). Statistical estimates first produced separately from the temporary and permanent samples, are being aggregated into a full estimate using a weighted average optimized for minimizing the variance term of one target estimate (the process is repeated for forest area, growing stock per hectare, harvested area, and volume).

The spatial features of this NFI design are presented in Fig. 5 (adapted and drawn from Ranneby et al. 1987, for one NFI region). It has been regularly adapted until some stabilization was met (Fridman et al 2014). The temporary clusters of a yearly sample are systematically distributed along regularly interpenetrating lines designed for a 10-year periodicity on a base square grid (Fig. 5a) that remind of early developments inspired by the Nordic *strip* design concept (Fridman et al. 2014). Their distribution is not even across space. The permanent clusters introduced later are distributed following a similar logic, though interpenetrating each other more regularly and drawing systematic parallelogram-shaped grids, identical across years, and revisited every 5 years (Fig. 5b). Their side size is $\sqrt{5}$ / $4\sqrt{5}$ km in the two directions. Temporary and permanent clusters are also interpenetrating each other. Consequently, the aggregation of permanent and temporary clusters of 1 year generates parallel and equally spaced blocks constituted of parallelogram-shaped grid cells of much lower size (Fig. 5c). These may be viewed as hyper-clusters, and the sampling design considered as a spatially systematic double cluster sampling. By comparison to previous designs, the Swedish design appears to be more sophisticated, and borrows to both strip and grid sampling.

2.6 As true as 5 = 4 + 1—the Romanian NFI and the cautious balance of annual and periodic priorities

The Romanian NFI is presented extensively in Bouriaud et al. (2020). Thorough graphical representations of the sampling design are further provided in Bouriaud and Marin (2016). This NFI is one of the latest NFIs implemented in Europe and relies on a cycle of 5 years, with a first cycle initiated in 2008. The Romanian inventory design borrows many features from those of other countries, including the interpenetrating panel approach, but has produced a specific design. The major originality of the Romanian NFI is to base its annual sampling on a spatial grid split into 4—not 5—interpenetrating yearly sampling panels, assessed during the first 4 years of the cycle, leaving the 5th year as a buffer year intended: (i) to absorb any delay in inventory operations of the 4 first years, (ii) to prepare and test for changes to these operations implemented in the next cycle, (iii) to elaborate the forest inventory statistics delivered every 5 years, and (iv) as a theoretical option not used to date, to sample additional temporary plots intended to increase the statistical precision in some forest contexts, or for the targeted sampling of forest disturbances. This inventory therefore copes up with annual sampling and 5-year cyclicity fundaments, while adopting a flexibility principle able to handle the difficulties of rigid yearly paneling as encountered in, e.g., the US (van Deusen 2002; Roesch 2018) and the French inventories (Bouriaud et al. 2023; see associated sections).

In details, two base grids of distinct resolutions (4 km side size in hill and mountain strata, 2 km side size in lowlands where forests are of scarcer occurrence) are implemented. These grids are not square but rhomboidal—every second line of sampling units being shifted by half the side size—to avoid their right-angle alignment in the face of mountain ridges that are mainly oriented in N-S and W-E directions across the country (Fig. 6). Therefore, the distances between adjacent sampling units after a full inventory cycle are 4/4.47 km, and 2/2.23 km, depending on the grid density and the directions of the grid. The even fractionation of this grid into 4 annual panels yields sub-grids constituted of parallelogram-shaped cells in a way similar with the Swedish and US forest inventories, with the difference that they exhibit one single orientation (Fig. 6). The distances between adjacent sampling units of one panel are ~ 7 km/ ~ 9 km ($2\sqrt{13} = 7.21$ km, $2\sqrt{20}$ km = 8.94 km) for the 4 × 4 km base grid, and ~ 3.5 km/ ~ 4.5 km ($\sqrt{20}$ km) for the 2 × 2 km base grid.

The sampling units are formed by square clusters of 4 permanent field plots positioned at each node of the grids, hereby implementing the option of a continuous inventory. Sampling is performed without further randomization, in a way therefore comparable to the Polish and Norwegian NFIs, clusters of the US FIA inventory being randomized in their locations.

Statistical estimations are based on either a single yearly panel, or by merging all 4 panels into one single sample for inference at the end of the cycle (Bouriaud et al. 2020). In view of the disruption introduced by the buffer year, no moving window estimator is implemented.

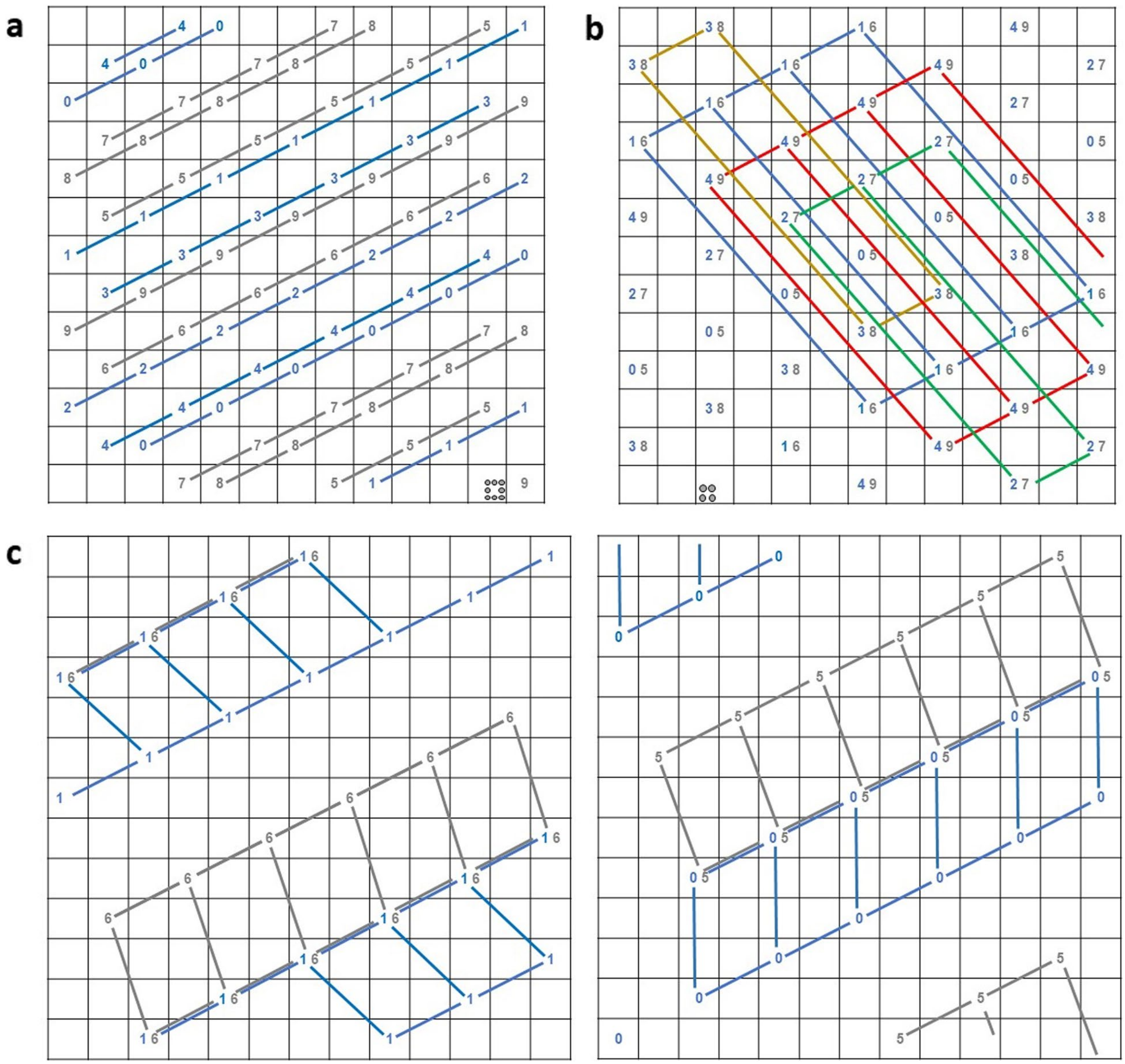

Fig. 5 Spatial design of the Swedish annual forest inventory survey as implemented initiated in 1953 and stabilized since 2003 (example of NFI region 3). The spatial design relies on a base grid of 5 km side size (Fridman et al. 2014). **a:** Temporary plot clusters are arranged as regularly spread strips across the grid (two cycles of 5 successive samples (0–4 and 5–9) are highlighted in blue/gray, respectively), with clusters of 8 plots as figured out bottom right of **a**, **b**: permanent plot clusters (four plots, bottom left) are positioned in between temporary strips in a way that they form parallelogram-shaped annual grids both interpenetrating each other and temporary strips (4 annual grids of permanent clusters out of 5, of different colors illustrated), **c:** the densification provided by assembling temporary (**a**) and permanent (**b**) plot clusters is illustrated for two couples of samples, each with a 5-year distance between samples (0–5 and 1–6). They form bands of parallelogram-shaped cells regularly spread over the territory and interpenetrating across years

While it may be theoretically possible (across a 5-year period and 4 panels), changes in the inventory operations planned at the end of each cycle lead to avoiding the mixing of sampling panels from different cycles. Since the issue of disruption in the inventory operations is immanent to all inventories and justifies the notion of cycle, it is surprising that it remains little discussed in the widespread application of the moving-window estimator.

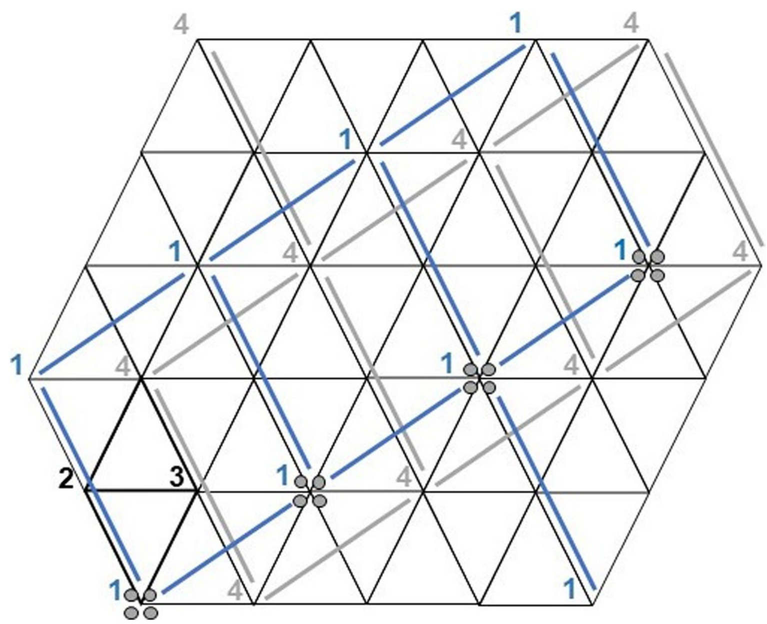

Fig. 6 Spatial design of the Romanian annual forest inventory survey as initiated in 2008. The sampling design relies on a rhomboid grid pattern resulting from the shifting of every two lines of grid nodes from half the side size of a square grid (in black). A rhomboid associating sampling units of the four annual panels (numbered from 1 to 4) is highlighted (bold black). Clusters of 4 permanent plots are positioned at each grid node. The rhomboid grid is fractionated in 4 systematic panels constituted of parallelogram-shaped cells (panels of years 1/4 figured out in blue / light gray, respectively). Panels 1/2 and 3/4 share common sampling directions, which is not the case of any combination of two other panel. (Elaborated and drawn from Bouriaud et al. 2020)

3 Main outcomes and discussion

3.1 Common design and inference properties, but no standard

This review of sampling designs and estimation processes of six *annual* national forest inventories highlights the existence of a common set of core sampling and inferential principles adopted to achieve this objective, namely: (i) the systematic interpenetrating panel design approach, whereby each annual sample ensures a balanced spatial cover of a country's forests, and samples are negatively coordinated to minimize the overlap between sampling units of successive samples and to maximize spatial cover (Grafström and Matei 2015), (ii) the systematic resort to regular base grids (see Figs. 1, 2, 3, 4, 5 and 6) from which the panel geometry is derived, with exclusion of other tessellation approaches (e.g., compact geographical stratification directed toward prior information of the population distribution, Walvoort et al. 2010), (iii) the possibility of fractionating the grid tessellations into 5 panels (hexagonal tessellation of the US NFI, square grids of the French, Norwegian and Polish NFIs). A noticeable exception is the rhomboid-based approach of the Romanian NFI (another one is the fractionation into 9 panels based on a square grid in Switzerland; Fischer and Traub 2019), (iv) the possibility to perform statistical inference on a true annual basis based on one single sampling panel, i.e., the fundamental *beat* of these inventory designs, (v) options for integrating successive panel samples into one reference estimation for a given 5-year period, which form the so-called *bar* of these designs, and appears especially relevant for international forest reporting processes. Nevertheless, substantial variations in these different approaches were also identified that suggest that it does not fully endorse the status of a *standard* (Fridman et al. 2014). This is made obvious from the synoptic comparison of these designs according to the different criteria reviewed (see Table 1).

3.2 Temporal surveys with units of different temporal status

A first major distinction should be made as regards the status of field sampling units: temporary or permanent, or a mix of both. While some inventory surveys are based exclusively on permanent sampling units (Poland, USA, Romania), other inventories are based on a mixed-strategy, where permanent and temporary units are associated, either at a cluster level within each annual panel (Norway) or at a panel level, with a distinct grid scheme (Sweden), or are based exclusively on semi-permanent sampling units (France, Table 1). In strategies where only permanent sampling units are found, the design makes profit from a spatially balanced spreading of annual samples to favor population coverage, and from the longitudinal nature of the information collected periodically on one given panel, for the estimation of forest changes. This approach is also found in the Swiss (Brändli et al. 2020) and the Belgian annual NFIs (Rondeux et Lecomte 2010). Yet, permanent plot samples of successive panels remain independent, questioning the continuity of forest change appraisal across years.

Temporary units compensate for possible imbalances in the population coverage provided by permanent grid schemes, which is a crucial aspect when the forest cover is extending (Bontemps 2021). The approach seems especially effective when distinguishing temporary and permanent units at a panel level (Sweden, Fig. 5). In the case of France, the limitation of using temporary units exclusively for measuring forest changes has been compensated for in 2010, with the introduction of sampling unit re-measurement (semi-permanent units, Bouriaud et al. 2023) after each period of 5 years, which appears to be original across NFI surveys. The same logic was at the origin of permanent sampling unit introduction in the Swedish inventory.

3.3 Unaligned systematic sampling strategies and their effectiveness

A second distinction concerns what exactly is referred to by *systematic* sampling, and the incentives taken to avoid unalignment. The underlying idea of unaligned systematic sampling remains to avoid sampling bias with respect to linear patterns or artifacts in the forest population. Unaligned sampling can be achieved in two main and non-exclusive ways, consisting in basing annual samples on a non-aligned grid paneling (e.g., Norway, USA, Figs. 3 and 4), or randomizing the location of field sampling units (USA, France, Sweden for temporary plot clusters, see Figs. 1, 3, and 5). In addition, we propose that plot clustering, which is beforehand a way to optimize field data collection by reducing traveling costs across sampling units while favoring between-plot variability (de Vries 1986), may also be seen as a means to deviate from perfect alignment.

A large array of strategies is seen implemented among panelised annual inventories (Table 2), ranging from perfect alignment (e.g., Poland or Romania, Figs. 2 and 6, also encountered in the Swiss and Belgian NFIs, see Table 2) to non-alignment as ensured at both stages (with USA as an exception, Fig. 3). Intermediate approaches target the grid level (e.g., Norway, Fig. 4) or the sampling unit level (France, Fig. 1) corresponding to an additional degree of randomness in sampling unit selection, or so-called sampling *stage*.

In the case of perfect alignment, a sampling strategy exclusively based on permanent sampling units is therefore at risk of giving a permanent status to potential spatial bias (Romania, Poland, to which the Swiss and Belgian NFIs can be added, see Table 2). Resort to sampling renewal based on temporary sampling unit is also identified as a rare strategy (France, Sweden, Table 2). In the Nordic Swedish and Finnish (Tomppo et al. 2010) NFIs, unaligned sampling is practiced across temporary plot clusters, and breaks the alignment of permanent plot clusters.

Whether unaligned systematic sampling may better perform than the aligned one, and the extent to which some among the highlighted options may better secure sample and estimation unbiasedness remains however hard to decide theoretically, as it will depend on the nature and extent of spatial structures in the population, and correlation patterns encountered (Matérn 1986). This is discussed below.

3.4 The 5-year moving window and the challenges of cycle homogeneity and annual inference

While more consensual, the third distinction concerns the statistical estimation process associated to annual paneling. Though sample paneling is initially intended to enable statistical inference at the annual temporal scale for a more reactive delivery of survey statistics, most inventory surveys indicate that the size of annual samples is often insufficient in practice to yield comprehensive and accurate estimates for small domains under scrutiny (e.g., at the level of administrative units). Here, a noticeable aspect is the strong comparability of the sampling effort across reviewed inventories, with an order of magnitude of 10 km for the distance between adjacent sampling units of one panel, regardless of differences in forest complexity and topography among these countries (Table 1).

An option to face the difficulty is to allow inference only for regional to country-level totals or averages (Breidenbach et al. 2020). For this reason, estimations over successive annual panels are most often aggregated, with the 5-year moving-average estimator as a consensus (Table 1). Other options include the so-called *time-indifferent* (TI) estimator (Reams et al. 2005), whereby successive samples are aggregated to form a unique one able to deliver a single more robust estimate of one population parameter. This approach is also implemented in the cyclic inventory of Romania (Table 1).

Nevertheless, limits to the moving-average estimator have been identified (van Deusen 2002; Roesch et al. 2005; Hou et al. 2021), with estimations lagging behind true population trends, and bringing the paradox that annual inventories remain hardly used for supporting an effective trend monitoring (De Gruijter et al. 2006). In addition, the idea that fixed-term reporting at dates distant from 5 years (cycle) can coexist with the continuous moving-window approach has been often encountered across the reviewed NFI systems, especially to fix periods during which protocols are maintained constant. In some cases, priority set on this objective can limit resort to the moving-window approach. In the Romanian inventory, a 5-year moving-window approach could hence be implemented in theory despite the existence of only 4 annual fractions, but it remains prohibited to avoid cycle-driven disruptions in the statistics arising from inventory operation shifts.

Two complementary strategies can thus be highlighted that intend to enhance the delivery of annual forest statistics. One first approach has been termed *multisource* inventory (Tomppo et al. 2008), as it intends to enhance the accuracy of NFI estimations by exploiting high resolution auxiliary information from remote sensing technologies. It proves especially efficient for a restricted set of dimensional variables such as the growing stock or the aerial biomass. Flux variables such as the net increment are matter of research and require longitudinal data (Vega and Saint-Onge 2008). Also, various approaches are found competing between each other to date (model-assisted, model-based, and hybrid inference; see Ståhl et al. 2016) and are too recent to suggest a consensus, together with being technically demanding. Alternatively, imputation techniques (Little and Rubin 1987) for inventory updating (van Deusen 1997) may be more tractable, but remain of a surprisingly restricted use in the target situation of panel analysis across the annual NFI programs reviewed. When plots are permanent, the principle is to make use of the most recent panel(s) remeasured over the design period, to calibrate a regression model of a given quantity (e.g., growing stock per hectare), and to apply it to panels intended to be measured in the coming years, in proportion to the time interval they are separated from the target year. In this manner, all panels are used for any point estimation in time, greatly increasing its precision. A few examples of implementation for cross-cycle inventory updating are given by Condés and McRoberts (2017) and Magnussen et al. (2017). The approach has been recently explored for the Swiss annual forest inventory, owing to its long 9-year period (Magnussen 2024, comm. pers.)

3.5 Annual inventories and the pitfall of a never-ending mechanics

Despite their advantages, the previous coordinated designs and their estimation processes require the maintenance of a temporal regularity and a similar sampling effort intensity over the long term. As such, these surveys are therefore prone to budget- or environment-driven disturbances (van Deusen 1999; Bouriaud et al. 2023), or more generally to a wish to modify sampling designs with increasing availability of information of the populations under study, or with changing objectives (Overton and Stehman 1996). The history of the Swedish forest inventory survey and the changes implemented over time well illustrate those aspects (Fridman et al. 2014). The need to adapt the annual sampling effort has also been described in the US and French forest inventory surveys, whereby the completion of annual panels had been made impossible at some occasions, leading to the violation of the periodicity and systematicity principles, and possible spatial and temporal biases in the sampling and inference processes (Roesch and van Deusen 2013). Subpaneling options—i.e., where not all units of a panel are purposedly sampled, but remain distributed in a pseudo-systematic way—happened to be implemented in both inventories (Reams et al. 2005 in the FIA with discussion of different possible options, and Bouriaud et al. 2023 in France) to avoid these undesirable effects. Otherwise, when adaptations to the design are not implemented, the estimation framework can also be adapted for the mitigation of variable time intervals, as illustrated in Roesch (2018).

In this respect, avoiding complex sampling designs for the temporal survey of natural populations has been a strong general recommendation (De Gruijter et al. 2006). Accordingly, Overton and Stehman (1996) have advocated for avoiding sampling design complexification in such surveys, and for sticking to simple designs such as the annual SRS, in a view to favor adaptability, transparency, and a maximum use of data by non-statisticians. The available literature further shows that little consideration has been paid on design flexibility and resilience. The approach chosen by the Romanian NFI survey (Table 1, Bouriaud et al. 2020) is noticeable and inspiring in this respect, as it both complies with a 5-year periodicity and the paneling approach and fixes one "buffer" year every 5 years, with multiple effective or theoretical purposes: (i) absorption of delays in the inventory operations of the previous years, (ii) addition of temporary plots spread among the permanent plot network to densify the sample and contribute to unalignment, (iii) test and implement changes to the inventory operation protocols for the next cycle. In a context of growing uncertainty about the occurrence of large forest disturbances, the same buffer year may also be theoretically used for, e.g., more ad hoc disturbance-based sampling operations, when necessary, hereby providing an elegant solution to the tension formerly identified in the USA between the competing ideas of disturbance-oriented (Hansen et al. 1998) and annual inventory designs (van Deusen 1999, AFIS and SAFIS pilot NFI projects).

3.6 Sample coordination—the antagonistic purposes of inclusive spatial cover and trend monitoring

An open question also arises about the negative sample coordination found between successive annual panels, encountered in the reviewed NFI surveys, and its appropriateness for the general growing objective of forest monitoring.

The notion of sample coordination refers to the overlap between successive samples drawn from a population (i.e., a fraction of sampling units belonging to successive samples; Patterson 1950), and it can be either positive (favored overlap) or negative (avoided overlap). Extreme coordination configurations correspond to (i) constituting new samples at each occasion (temporary plots in forest inventory), which is especially useful for estimating population means when the population changes over time, or (ii) maintaining one same sample used at each occasion (permanent plots), most efficient for tracking population changes (Patterson 1950). Sampling with partial replacement of units is an intermediate approach imagined to satisfy both objectives, in the usual context where forest changes are slow (Ware and Cunia 1962). Negative spatial coordination is especially efficient when the spatial distribution of the population is both unknown and of complex spatial structure, and changes over time (Grafström & Matei 2018).

Whereas the initial intention of annual inventory designs is to permit a high-frequency update of forest status (i.e., *status monitoring*; De Gruijter et al. 2006), the availability of annual systematic samples has however rapidly supported the view of using such samples for monitoring population trends (i.e., *trend monitoring*; same reference) and their variations across a territory. The view is illustrated by, e.g., NFI-based monitoring approaches of forest growth (Elfving and Tegnhammar 1996; Ols et al. 2020, 2021), or of the growing stock (Bontemps et al. 2020; Henttonen et al. 2017).

For trend monitoring purposes, however, positive coordination across successive samples has been put forward as an advantage, as it reduces the variance of change estimation (Grafström and Matei 2018). It has also proven useful for establishing forest trends when survey protocols change over time (Goeking 2015). In multipurpose surveys like NFIs, design optimization is generally unobvious (De Gruijter et al. 2006), and defining the appropriate degree of spatial coordination between panels to address these two goals remains a largely uncovered issue among the reviewed inventories.

The combination of permanent sampling units and paneling concepts (Table 1) yet constitutes a basic sampling asset for handling the trade-off between spatial and temporal cover, with permanent plots revisited periodically (perfect coordination scheme) as a basis for trend estimation and monitoring, at least at a 5-year pace. From an inferential viewpoint, one perspective may be to systematize separate inference approaches (Fridman et al. 2014 for the Swedish NFI), and e.g. implement time-indifferent estimations for appraising forest status (Bechtold and Patterson 2005), and change estimations based on a difference estimator, every year. We however stress that this option is not particularly emphasized among the reference texts of reviewed inventories, and no dedicated estimation framework for changes is either discussed. This would deserve a specific focus (Roesch & van Deusen 2013). In the French inventory, where all sampling units are yearly renewed and semi-permanent, the issue is now being under scrutiny, with two major differences with the previous designs. First, the full renewal of samples every year favors the unbiased coverage of a forest population which is changing very fast (Bontemps et al. 2020). Second, the trend monitoring perspective has significance over 5 years, but cannot feed the elaboration of forest time series over the longer term.

We last wish here to formulate an original proposal, regarding a possible new use of the plot cluster design to strengthen the positive coordination of successive samples in panelized inventories, and turn their standard statistical weakness (correlation among neighbor units) as an asset. In clustered designs (Table 1), the distance between adjacent sampling units of one cluster is usually by a minimum one order of magnitude (Poland, Romania, Sweden, Finland, Tomppo et al. 2011) smaller than that separating clusters of successive panels (exceptions concern the Norwegian and Belgian inventories, with ratios of one third to one fourth, but that correspond more exactly to stratified spatial sampling; Rondeux et Lecomte 2010, Breidenbach et al. 2020). The within-cluster correlation can therefore be expected to be much greater than that between clusters, and in principle, so should be that of within-cluster forest changes. By substituting the prevailing paneling of one base periodic sampling grid for a within-cluster paneling strategy, systematic interpenetrating sampling would be maintained every year, with increased temporal coordination. One constraint would be to match the cluster size with that of the inventory period, or a multiple of it. Since logistic cost may be increased, careful quantitative analysis of the statistical gains and costs, and options for a design reformulation may be established. The question may be easier to address in inventories where the cluster size is large (typically around 10 sampling units or more).

3.7 Digital forest twins for the large-scale simulation and evaluation of sampling designs

Previous sections have highlighted diverse design options, and the extent to which a compared quantitative evaluation of these alternatives is largely missing to date, as it remains based on theoretical considerations or intuitions. This typically concerns (i) options for securing sample unalignment at different levels (Table 2), (ii) the status of the temporary/permanent sampling unit mix for meeting the spatial cover/temporal accuracy objectives, (iii) the degree and sign of coordination across panel samples, (iv) the role that clusters of sampling units can play regarding unalignment or sample coordination. Statistical estimation is also concerned in its temporal dimension, as regards moving-window, time-indifferent, and panel imputation approaches, also when it comes to the issue of the precision provided by annual sampling panels.

In this respect, there is a crucial need for simulation benchmarks questioning the efficiency of these alternate design strategies and inference frameworks, and primarily those that may be newly formulated from the present bases. While this need has been early stressed by some inventory authors (e.g., Roesch et al. 1993: *given the amount of time and money it takes to acquire data in forestry studies, the ability to easily test the properties of different sampling methods before they are applied in the field is of paramount importance.* [...] *Simulation of these schemes before implementation may help uncover overlooked problems*), the issue remains uncovered in the literature (but see Stamatellos and Panourgias 2005, on tree spatial distributions).

Noteworthy, substantial progress is now being accomplished in the field of *digital twinning* technologies, borrowed to industrial development (Tao and Qi 2019), and spreading to natural systems thanks to the unprecedented availability of high-resolution remote sensing products calibrated by inventory data. Recent reviews on the concept as applied to forests (Mõttus et al. 2021; Buoconore et al. 2022; Döllner et al. 2023) advocate for a predominant modeling and simulation objective (Sanchez-Guzman et al 2022), survey sampling remaining overlooked. Nevertheless, concern for large-scale forest digital twinning (Mõttus et al. 2021, Li et al. 2022), and for individual tree mapping (Li et al. 2022) suggest that these technologies may be soon available for sampling evaluation purposes. Their promotion for the future (re)design of forest surveys is thus a research direction to be strongly encouraged in the future.

3.8 Options for a *pan*-European forest inventory and monitoring design?

The recent elaboration of the new *European Forest Strategy for 2030* has fostered strong debates about the need for elaborating a pan-European forest observation and monitoring framework (European Commission 2021, Ferretti et al. 2021, Bontemps et al. 2022). Also, on the one hand, climatic and disturbance pressures on forests plead for a regularly—not to say annually—updated monitoring of forest status. On the other hand, European forest reporting process is established every 5 years. In the face of the emerging annual/5-year standard shared by reviewed annual forest inventories, we believe the fundamental bases for addressing the issue to be available (hence "take 5" may be a general recommendation). Two major challenges should nevertheless be addressed: (i) being able to elaborate and computationally test new spatiotemporal designs that would borrow the most promising ideas among existing ones, (ii) being able to resynchronize inventory operations conducted across different countries according to a common bar. In principle, this would not raise any strong concern for annual inventories—even those based on an alternate periodicity (e.g., the 9-year periodic Swiss inventory)—as any subset of successive systematic annual panels on a given temporal window should ensure a correct, albeit not perfect, spatial cover of forests under scrutiny (van Deusen 2002; Patterson and Reams 2005). The issue is however less obvious for cyclic inventory programs. While some of them are now envisioning a transition toward the annual inventory paradigm (e.g., in Ireland, McCullagh, comm. pers.), the lower precision of associated annual statistics makes it less acceptable in federal States where targets are defined at a provincial/state level (e.g., Spain, Germany).

4 Conclusions

- The *interpenetrating panel design* is the single one to date that ensures both a spatial balance and yearly fractionation on comparably sized subsamples. A standard is seen arising among the NFIs that have opted for this design, with unexpected convergence that includes a 5-year periodicity, a sampling design organized with interpenetrating annual panels, an annual sampling effort of an order of magnitude of 1 sampling unit per 50 to 100 km^2, and yearly statistics delivered based on a 5-year moving-window estimator.
- Despite this convergence, variations across the reviewed designs remain substantial, and concern the panel geometry, the practice of unaligned sampling, the resort to permanent/temporary sampling

units, and to clustering, questioning the existence of possible "best" options and their dependences on forest features and attributes. Some original designs also deserve attention. The Romanian NFI opens perspectives on handling difficulties inherent to annual inventory by using a periodic 1-year disruption in the recurrent inventory operations to serve several timely objectives. Also, the French NFI has adopted a sampling with a total replacement approach and a semi-permanent status of sampling units, allowing to remain inclusive of the whole forest population while permitting to track forest changes.

- The present review of such variations around a core principle also forms a helpful basis for countries aiming at finding an effective alternative to the traditional cyclic inventory approach, or wishing to plan a new inventory (the said "take 5"). It also calls for developing flexible simulation facilities of sampling designs at wide scale to support user's choices, an approach that may soon be supported by arising *digital twin* technologies.
- Most NFI designs include permanent plot samples of major importance for estimating forest changes. Nevertheless, the annual paneling of permanent plot networks, and their often-encountered admixture with temporary plots, questions the rationale and the inferential approaches used for estimating forest changes with a long-term continuity. This forms a critical issue in the uncertain future environmental era and calls for renewed research on this aspect.
- Difficulties are also identified concerning the maintenance of such a continuous approach over the long term, the frequent insufficiency of annual sample sizes for annual statistic delivery at a local scale, the issue of sample coordination for addressing trend monitoring issues, also the partial inability of the moving-window estimator to reflect true forest trends, with existing or emerging solutions explored in the review. It is however stressed that both aspects concur to a general tension between the purposes of (i) spatially representative and refreshed information on forest status and (ii) temporally reliable information to serve trend monitoring purposes. Research targeting new designs better complying with these challenges remains needed in this respect.
- The changes engaged by NFI programs since the beginning of the twentieth century demonstrate a substantial research dynamic that not only contributes to the field of survey sampling, but also provides a strong support to future incentives directed toward the forest threats arising from climate, environmental, and biotic changes. As such, it deserves attention and support from the authorities, in a stimulating political context in Europe.

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Authors' contributions
The review project was initiated from a discussion between the two authors. Jean-Daniel Bontemps performed the review, arising from Bouriaud et al. (2023) Journal of Vegetation Science 34:e13195, wrote the manuscript and designed the figures. Olivier Bouriaud widened the review to the Romanian NFI, contributed to the discussion section, and reviewed the manuscript. All authors reviewed and improved previous versions of this manuscript.

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Ethics approval and consent to participate
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Competing interests
The authors declare that they have no competing interests.

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References
Audinot T, Wernsdörfer H, Bontemps JD (2020) Ancient forest statistics provide centennial perspective over the status and dynamics of forest area in France. Ann for Sci 77:77. https://doi.org/10.1007/s13595-020-00987-5
Bechtold WA, Patterson PL (2005) The enhanced forest inventory and analysis program - national sampling design and estimation procedures. USDA Forest Service, GTR 80, Asheville
Bontemps J-D (2021) Inflation of wood resources in European forests: The footprints of a big-bang. PLoS ONE 16:e0259795. https://doi.org/10.1371/journal.pone.0259795
Bontemps J-D, Bouriaud O, Vega C, Bouriaud L (2022) Offering the appetite for forest monitoring a diversified diet. Ann for Sci 79:19. https://doi.org/10.1186/s13595-022-01139-7

Bontemps J-D, Denardou A, Hervé J-C, Bir J, Dupouey JL (2020) Unprecedented pluri-decennial increase in the growing stock of French forests is persistent and dominated by private broadleaved forests. Ann Forest Sci 77:98. https://doi.org/10.1007/s13595-020-01003-6
Bouriaud O, Marin G (2016) Romanian national forest inventory. 2nd international workshop on forest inventory statistics, 23–28 may 2016, Czech republic, Kromeriz, 28pp.
Bouriaud O, Marin G, Hervé JC, Riedel T, Lanz A (2020) Estimation methods in the Romanian national forest inventory. Nova Publishers, New-York
Bouriaud O, Morneau F, Bontemps JD (2023) Square-grid sampling support to reconcile systematicity and adaptivity in periodic spatial surveys of natural populations. J Veg Sci 34:e13195. https://doi.org/10.1111/jvs.13195
Brändli U-B, Abegg M, Allgaier Leuch B (2020) Inventaire forestier national suisse. Résultats du quatrième inventaire 2009–2017. Birmensdorf, Institut fédéral de recherches sur la forêt, la neige et le paysage WSL; Berne, Office fédéral de l'environnement. 341 pp. https://doi.org/10.16904/envidat.147
Breidenbach J, Granhus A, Hylen G, Eriksen R, Astrup R (2020) A century of National Forest Inventory in Norway – informing past, present, and future decisions. Forest Ecosystems 7:46. https://doi.org/10.1186/s40663-020-00261-0
Buoconore L, Yates J, Valentini R (2022) A proposal for forest digital twin framework and its perspectives. Forests 13:498. https://doi.org/10.3390/f13040498
Christianson DS, Kaufman CG (2016) Effects of sample design and landscape features on a measure of environmental heterogeneity. Methods Ecol Evol 7:770–782. https://doi.org/10.1111/2041-210X.12539
Ciais P, Reichtein M, Viovy N, Granier A, Ogée J, Allard V, Aubinet M, Buchmann N (2005) Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437:529–533. https://doi.org/10.1038/nature03972
Condés S, McRoberts RE (2017) updating national forest inventory estimates of growing stock volume using hybrid inference. For Ecol Manage 400:48–57. https://doi.org/10.1016/j.foreco.2017.04.046
Cornwall W (2016) Efforts to link climate change to severe weather gain ground. Science 351:1249–1250. https://doi.org/10.1126/science.351.6279.1249
De Gruijter J, Bierkens MFP, Brus DJ, Knotters M (2006) Sampling for natural resource monitoring. Springer, Berlin - Heidelberg
de Vries PG (1986) Continuous forest inventory with partial replacement of sample plots. In: de Vries PG (ed) Sampling Theory for Forest Inventory: A Teach-Yourself Course. Springer, Berlin, pp 141–160
Döllner J, Amicis (de) R, Burmeister J-M, Richter R (2023). Forests in the Digital Age: Concepts and Technologies for Designing and Deploying Forest Digital Twins. In The 28th International ACM Conference on 3D Web Technology (Web3D '23), October 09–11, 2023, San Sebastian, Spain. ACM, New York, NY, USA, 12 p. https://doi.org/10.1145/3611314.3616067
Elfving B, Tegnhammar L (1996) Trends of tree growth in Swedish forests 1953–1992: An analysis based on sample trees from the national forest inventory. Scand J for Res 11:26–37. https://doi.org/10.1080/02827589609382909
European Commission (2021) New EU Forest Strategy for 2030. Brüssels, 27 pp. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021DC0572
Ferretti M (2021) New appetite for the monitoring of European forests. Ann for Sci 78:94. https://doi.org/10.1007/s13595-021-01112-w
Fischer C, Traub B (2019) Swiss national forest inventory – methods and models of the fourth assessment. Springer, Cham
Fridman J, Holm S, Nilsson M, Nilsson P, Ringvall AH, Ståhl G (2014) Adapting National Forest Inventories to changing requirements – the case of the Swedish National Forest Inventory at the turn of the 20th century. Silva Fennica 48:1095. https://doi.org/10.14214/sf.1095
Gillespie AJR (1999) Rationale for an annual forest inventory program. J Forest 97:16–20. https://doi.org/10.1093/jof/97.12.16
Goeking SA (2015) Disantangling forest change from forest inventory change: a case study from the US interior West J For 113:475–483. https://doi.org/10.5849/jof.14-088
Grafström A, Matei A (2015) Coordination of conditional Poisson samples. J Official Statistics 31:649–672. https://doi.org/10.1515/jos-2015-0039
Grafström A, Matei A (2018) Coordination of spatially balanced samples. Surv Methodol 44:215–238
Hansen MH, Schreuder HT, Heinzen D (1998) Selection of plot remeasurement in an annual inventory. Integrated tools conference proceeding. USDA Forest Service, GTR 212, Boise, pp. 67–78
Henttonen HM, Nöjd P, Mäkinen H (2017) Environment-induced growth changes in the Finnish forests during 1971–2010 – An analysis based on National Forest Inventory. For Ecol Manage 386:22–36. https://doi.org/10.1016/j.foreco.2016.11.044
Hervé JC (2016) Forest inventory of France. In: Vidal C, Alberdi I, Hernández L, Redmond J (eds) National Forest Inventories - pathways for common reporting. Springer, Cham, Switzerland, pp 385–404
Hlásny T, König L, Krokene P, Lindner M, Montagné-Huck C, Müller J, Qin H, Raffa KF, Schelhaas M-J, Svoboda M, Viiri H, Seidl R (2021) Bark Beetle Outbreaks in Europe: State of Knowledge and Ways Forward for Management. Curr Forestry Rep 7:138–165. https://doi.org/10.1007/s40725-021-00142-x
Hou Z, Domke GM, Russell MB, Coulston JW, Nelson MD, Xu Q, McRoberts RE (2021) Updating annual state- and county-level forest inventory estimates with data assimilation and FIA data. For Ecol Manage 483:118777. https://doi.org/10.1016/j.foreco.2020.118777
Houllier F (1985) Inventaires successifs en forêt : intérêt théorique et limites pratiques de l'échantillonnage partiellement renouvelé. Ann for Sci 42:245–264
Johnson DS, Williams MS, Czaplewski RL (2003) Comparison of estimators for rolling samples using forest inventory and analysis data. Forest Science 49:50–63. https://doi.org/10.1093/forestscience/49.1.50
Lecomte H, Rondeux J (1991) Les inventaires forestiers nationaux en Europe : tentative de synthèse (Part 1). Silva Belgica 98:13–19
Li S, Brandt M, Fensholt R, et al (2022) Digital twinning of all forest and non-forest trees at the national level via deep learning. Research Square https://europepmc.org/article/ppr/ppr497328
Little RJA, Rubin DB (1987) Statistical analysis with missing data. Wiley, Hobiken, New-Jersey
Magnussen S (2024) Panel analysis with imputations. Swiss NFI workshop, WSL, Birmensdorf, Switerland, 24 p.
Magnussen S, Stinson G, Boudewyn P (2017) Updating Canada's National Forest Inventory with multiple imputations of missing contemporary data. For Chron 93:213–225. https://doi.org/10.5558/tfc2017-030
Mahalanobis PC (1946) Recent experiments in statistical sampling in the Indian statistical institute. J Roy Stat Soc 109:329–397
Matérn B (1986) Spatial variation. Springer, New-York
Meyfroidt P, Lambin EF (2011) Global forest transition: prospects for an end to deforestation. Annu Rev Environ Resour 36:343–371. https://doi.org/10.1146/annurev-environ-090710-143732
Michalak R, Zajączkowski R (2010) Forest Inventory of Poland. In: Tomppo E, Gschwantner T, Lawrence M, McRoberts R (eds) National forest inventories - pathways for common reporting. Springer, Heidelberg, Dordrecht, London, New-York, Heidelberg, pp 425–436
Mõttus M, Dees M, Astola H, et al. (2021) A methodology for implementing a digital twin of the Earth's forests to match the requirements of different user groups. GI_Forum 1 :130–136. https://doi.org/10.1553/GISCIENCE2021_01_S130
Munholland PL, Borkowski JJ (1996) Simple Latin square sampling + 1: a spatial design using quadrats. Biometrics 52:125–136. https://doi.org/10.2307/2533150
Ols C, Gschwantner T, Schadauer K, Bontemps JD (2021) Unexpected negative effect of available water capacity detected on recent conifer forest growth trends across wide environmental gradients. Ecosystems 25:404–421. https://doi.org/10.1007/s10021-021-00663-3
Ols C, Hervé JC, Bontemps JD (2020) Recent growth trends of conifers across Western Europe are controlled by thermal and water constraints and favored by forest heterogeneity. Sci Total Environ 742:140453. https://doi.org/10.1016/j.scitotenv.2020.140453
Olsen AR, Sedransk J, Edwards D, Gotway CA, Liggett W, Rathbun S, Reckhow KH, Young LJ (1999) Statistical issues for monitoring ecological and natural resources in the United States. Environ Modell Assess 54:1–45. https://doi.org/10.1023/A:1005823911258
Overton WS, Stehman SV (1996) Desirable design characteristics for long-term monitoring of ecological variables. Environ Ecol Stat 3:349–361. https://doi.org/10.1007/BF00539371
Owens PJ (1987) Knight's move squares. Discret Math 63:39–51

Patterson HD (1950) Sampling on successive occasions with partial replacement of units. J Roy Stat Soc B 12:241–255. Contribution from Oxford University Press. https://www.jstor.org/stable/2983982
Patterson PL, Reams GA (2005) Combining panels for forest inventory and analysis estimation. In: Bechtold WA, Patterson PL (eds) The enhanced forest inventory and analysis program - national sampling design and estimation procedures. USDA Forest Service, GTR 80, Asheville, pp. 69–74
Quenouille MH (1949) Problems in plane sampling. Ann Math Stat 20:355–375. https://www.jstor.org/stable/2236533
Ranneby B, Cruse T, Hagglund B, Jonasson H (1987) Designing a new national forest survey for Sweden. Studia Forestalia Suecica 177:1–28
Reams GA, Smith B, Bechtold WA, McRoberts RE, Spirek F, Liff C (2005) Three proposed data collection models for annual inventories. In: McRoberts RE, Reams GA, van Deusen PC, McWilliam W (eds) Fifth annual forest inventory and analysis symposium 2003, New Orleans. USDA Forest Service. GTR 69, pp. 1–7
Reams GA, van Deusen PC (1999) The Southern annual forest inventory system. J Agric Biol Environ Stat 4:346–360. https://doi.org/10.2307/1400494
Roesch FA (2018) Composite estimators for growth derived from repeated plot measurements of positively-asymmetric interval lengths. Forests 9:427. https://doi.org/10.3390/f9070427
Roesch FA, Green EJ, Scott CT (1993) An alternative view of forest sampling. Survey Method 19:199–204
Roesch FA, Reams GA (1999) Analytical alternatives for an annual inventory system. J Forest 97:33–37. https://doi.org/10.1093/jof/97.12.33
Roesch FA, Steinman JR, Thompson MT (2005) Annual forest inventory estimates based on the moving average. In: McRoberts RE, Reams GA, van Deusen PC, McWilliam W (eds) Fifth annual forest inventory and analysis symposium 2003, New Orleans. USDA Forest Service. GTR 69, pp. 21–30
Roesch FA, van Deusen PC (2013) Time as a Dimension of the Sample Design in National-Scale Forest Inventories. Forest Science 59:610–622. https://doi.org/10.5849/forsci.12-075
Rondeux J, Lecomte H (2010) Inventaire permanent des ressources forestières de Wallonie (IPRFW) – guide méthodologique. Direction générale opérationnelle de l'Agriculture, des Ressources naturelles et de l'Environnement Département de la Nature et des Forêts, May 2010, 163 p. https://hdl.handle.net/2268/109282
Sanchez-Guzman G, Velasquez W, Alvarez-Alvarado MS (2022) Modeling a simulated Forest to get Burning Times of Tree Species using a Digital Twin. *IEEE 12th Annual Computing and Communication Workshop and Conference (CCWC),* Las Vegas, NV, USA, 2022, pp. 639–643. https://doi.org/10.1109/CCWC54503.2022.9720768
Seidl R, Schelhaas M-J, Lexer MJ (2011) Unraveling the drivers of intensifying forest disturbance regimes in Europe. Glob Change Biol 17:2842–2852. https://doi.org/10.1111/j.1365-2486.2011.02452.x
Ståhl G, Saarela S, Schnell S, Holm S, Breidenbach J, Healey SP, Patterson PL, Magnussen S, Næsset E, McRoberts RE, Gregoire TG (2016) Use of models in large-area forest surveys: comparing model-assisted, model-based and hybrid estimation. Forest Ecosystems 3:5. https://doi.org/10.1186/s40663-016-0064-9
Stamatellos G, Panourgias G (2005) Simulating spatial distributions of forest trees by using data from fixed area plots. Forestry 78:305–312. https://doi.org/10.1093/forestry/cpi028
Stevens DL, Olsen AR (2004) Spatially balanced sample of natural resources. J Am Stat Assoc 99:262–278. https://doi.org/10.1198/016214504000000250
Talarczyk A (2014) National forest inventory in Poland. Balt for 20:333–341
Tao F, Qi Q (2019) Make more digital twins. Nature 573:490–491. https://doi.org/10.1038/d41586-019-02849-1
Tinkham WT, Mahoney PR, Hudak AT, Domke GM, Falkowski MJ, Woodall CW, Smith AMS (2018) Applications of the United States forest inventory and analysis dataset: a review and future directions. Can J for Res 48:1–18. https://doi.org/10.1139/cjfr-2018-0196
Tomppo E, Gschwantner T, Lawrence M, McRoberts R (2010) National Forest Inventories. Pathways for common reporting. Springer, Heidelberg
Tomppo E, Haakana M, Katila M, Peräsaari J (2008) Multi-source national forest inventory – methods and applications. Springer, Heidelberg, Dordrecht ,London, New-York, https://doi.org/10.1007/978-90-481-3233-1
Tomppo E, Heikkinen J, Henttonen HM, ihalainen A, Katila M, Mäkelä H, Tuomainen T, Vainikainen N, (2011) Designing and conducting a forest inventory – case: 9th national forest inventory of Finland. Springer, Dordrecht Heidelberg London New-York
Tomppo E, Tuomainen T (2010) Country report of Finland. In: Tomppo E, Gschwantner T, Lawrence M, McRoberts R (eds) National forest inventories - pathways for common reporting. Springer, Heidelberg, Dordrecht, London, New-York, pp 185–206
Tomter SM, Hylen G, Nilsen J-E (2010) Forest inventory of Norway. In: Tomppo E, Gschwantner T, Lawrence M, McRoberts R (eds) National forest inventories - pathways for common reporting. Springer, Heidelberg, Dordrecht, London, New-York, pp 411–424
van Deusen PC (1997) Annual forest inventory statistical concepts with emphasis on multiple imputation. Can J for Res 27:379–384. https://doi.org/10.1139/x96-211
van Deusen PC (1999) Pros and cons of the interpenetrating panel design. In: McRoberts RE, Reams GA, van Deusen PC (eds) Proceedings of the 1st annual forest inventory and analysis symposium. USDA Forest Service, GTR 213, San Antonio, pp. 14–19
van Deusen PC (2002) Comparison of some annual forest inventory estimators. Can J for Res 32:1992–1995. https://doi.org/10.1139/x02-115
Vega C, Saint-Onge B (2008) Height growth reconstruction of a boreal forest canopy over a period of 58 years using a combination of photogrammetric and lidar models. Remote Sens Environ 112:184–1794. https://doi.org/10.1016/j.rse.2007.09.002
Vidal C, Alberdi I, Hernández L, Redmond J (2016) National forest inventories. Assessment of wood availability and use. Springer, Cham
Vidal C, Bélouard T, Hervé JC, Robert N, Wolsack J (2005) A new flexible forest inventory in France. In: McRoberts RE, Reams RA, van Deusen PC, McWilliams WH (eds) Seventh annual forest inventory and analysis symposium 2005. USDA Forest Service, GTR 77, Portland, pp. 67–73
Walvoort DJJ, Brus DJ, de Gruijter JJ (2010) An R package for spatial coverage sampling and random sampling from compact geographical strata by k-means. Comput Geosci 36:1261–1267. https://doi.org/10.1016/j.cageo.2010.04.005
Ware KD, Cunia T (1962) Continuous inventory with partial replacement of samples. Forest Sci Monogr 3:1–40
Westfall JA, Coulston JW, Moisen GG, Andersen H-E (2022) Sampling and estimation documentation for the Enhanced Forest Inventory and Analysis Program. USDA Forest Service, GTR 207, Madison

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