The National Forest Inventory in Germany: Responding to Forest-Related Information Needs*)

(With 2 Figures and 5 Tables)

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1. INTRODUCTION

National Forest Inventories (NFIs) traditionally produce forest-related data and information at the national and subnational levels. They are meant to support decisions in forest-related policies and discussions in the general public. They are also meant to feed into international reporting obligations and to provide valuable and unique input for research. Commonly, the data produced from NFIs are based on scientific methods. In the ideal case, when all parties are acknowledging science-based data, NFI results help to generate a detailed picture of the forests, their status, and their developments at the national level – and help to reduce forest-related speculations.

Though stand and district-level forest assessments, one fundament of forest management, have a long history, an explicit demand for large-area and national-level forest information has likely only arisen about 150 years ago. For smaller areas, expert-based assessments were feasible and frequently implemented with foresters visiting and describing all stands of interest. This is more difficult for the forests in large areas, for example, in whole countries. For such a large area, covered by a wide variety of site conditions, sample-based approaches were the only method at the time. While sample plots were already in wide use in forestry in the 19th century, and were described as an intuitive and efficient approach to generate standlevel information, a formalized technique of statistical sampling for large populations was only developed, and gradually accepted, as a methodology to produce valid results around the year 1900. In 1895, the Norwegian statistician A.N. KIAER (KIAER, 1895–96; cited after BETHLEHEM, 2009) presented a sampling approach that was then called, "the representative method", where "representativeness" played a central role. KIAER did not, however, clearly define what that meant for the process of selecting samples. At the time, purposive expert selection of samples was acceptable, even though it appeared that systematic sampling was frequently applied (BETHLEHEM, 2009). This approach was possibly considered a sort of "natural approach" to guarantee "representativeness". KIAER, for example, applied this approach in 1895 to do a survey of Norwegian workers (STEPHAN, 1948). Systematic sampling on parallel strip-plots was also employed in the early national forest inventories in the European Nordic countries. Probabilistic sampling, predominantly used as the basis for sampling today, was introduced by the English statistician Bowley some years later and was formally presented by him in 1924 (BOWLEY, 1906, 1926; cited after SENG, 1951). However, it was the influential 1934 paper by the Polish statistician Neyman (cited after STEPHAN, 1948), which eventually established probabilistic sampling, and its possibilities to estimate confidence intervals, as the basis of scientific sampling (in this context, however, the parallel developments in sampling science in Russia are hardly cited; see BETHLEHEM 2009). The early intuitive tendency toward systematic sampling for the sake of "representativeness" has proven to be the preferred method until today: systematic sampling is preferred practically everywhere over pure probabilistic (randomized) sampling for forest monitoring. While the challenge of unbiasedly estimating variances from a systematic sample remains unsolved, it is known from many studies that, given the same "sampling efforts", systematic sampling yields more precise estimates under practically all conditions in forest monitoring. It is thus more "representative" than sampling

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*) This article is dedicated to our esteemed colleague Prof. Dr. WALTER SCHÖPFER, energetic promotor of the German NFI idea since the 1970s and 1980s, on the occasion of his 90th birthday – with the best wishes.

designs based on simple random sampling. An early simulation study on the comparison of random and systematic sampling in forest inventory was done by PRODAN (1958), and MATÉRN (1960) provided theoretical foundations. The term "representative" is not used anymore as a strategy for sample selection, even though it remains, of course, a major characteristic of a good sampling design. KRUSKAL and MOSTELLER (1979a, 1979b, 1979c, 1980) elaborated, very instructively, in a series of four articles on the use of the term "representative" in sampling.

NFIs were among the early, large-area applications of such statistical sampling, even though they are hardly mentioned in the literature about the history of sampling where the focus is commonly more on population censuses and economic surveys. The forest inventory statisticians at that time made significant contributions to the analysis of systematic line sampling (LINDEBERG, 1923; LANGSAETER, 1926). The first NFI that was rooted in statistical sampling was implemented in 1919–1930 in Norway. This was followed by other Nordic European countries in the early 1920s: Finland in 1921–1924 (METLA, no date) and Sweden in 1923–1929 (AXELSSON et al., 2010). Of course, there were precursors for larger-area forest inventories. For example, Dietrich Brandis' large-area teak inventory in Burma (todays Myanmar) in the 1860s (HESMER, 1975), which used strip plots crossing the whole inventory region. This was also practiced by, for example, af STRÖM (1830, cited after NÄSLUND 1982) for Sweden and by KÖNIG (1835) for Germany. For small-area forest inventory, the use of "representative plots" to learn about the whole of the forest has long been in use (mentioned, for example, as an established technique by HEYER, 1861 and ZETZSCHE, 1891). However, all these early inventory studies lacked a rigorous statistical basis of sampling design and analysis.

Today, NFIs may be considered the standard data source for national forest-related data and they are the base input for international reporting on forests in the framework of international conventions. In UN-FCCC (United Nationals Framework Convention on Climate Change), for example, NFIs are referred to as core elements of national forest monitoring systems, which are to be implemented in countries that wish to report on their forest carbon emission reductions and participate in REDD+ (UN-FCCC decision 11/CP.19: modalities for national forest monitoring systems). Many countries carry out NFIs; and FAO is supporting developing countries in building corresponding capacity and expertise (NEEFF and PIAZZA, 2019). Harmonization of definitions, methodological approaches that integrate various data sources and models, and reporting formats are crucial topics when international reporting is at stake. For Europe, a comprehensive compilation and comparison of NFI approaches has been produced in COST Action E43 (TOMPPO et al., 2010), comparing methodologies and suggesting pathways for harmonization. From this comparison, it becomes clear that the implementation of regular NFIs in Germany, on a statistical basis,was delayed in comparison with other countries in Europe: 1987 is the reference year for the first NFI in the Federal Republic of Germany.

In this paper, background, history, and current developments of the German NFI are described. This paper was inspired by the very instructive paper of FRIDMAN et al. (2014), who offered such a view for the Swedish NFI. The German case may be instructive as well, because the overall framework conditions are quite different from those in Sweden.

2. SOME BACKGROUND ON FORESTS AND FORESTRY IN GERMANY

The most recent, 3rd German NFI (now commonly referred to as "BWI 2012") estimated the forest cover of Germany at 32.0% (relative standard error SE% = 0.7%) which corresponds to an estimated total area of 11.42 million ha. After agricultural lands, forests cover the second largest portion of land use in Germany. Germany is a densely populated country with 83 million people (translating into 2.3 people per hectare or 7.3 people per hectare of forest). In its long history of land uses, all forests are assumed to have been utilized and managed in some way, so that there is no truly virgin forest remaining. However, many forests today have a diverse structure with multiple layers and mixed species compositions and have a "quite close-to-nature appearance". This is a result of the long-standing silvicultural strategy of close-to-nature forest management, which has the goal to re-establish close-to-nature mixed forests wherever the conditions permit. German forestry follows the principle of multipurpose forestry, meaning that all forest functions should be provided by all forests. There is no separation of production function and conservation, but there is some prioritization for special areas like the large national parks, and other protected forest areas. These combined areas currently cover 4.1% of the accessible forest area in Germany (BMEL, 2014) where timber production has been suspended. For 2012, the average growing stock over all forests and all ownership types was estimated to be 336 m^3ha^{-1} (SE% = 0.4%), and total growing stock is among the highest of European countries (BMEL, 2014). Mean annual increment was estimated at 10.85 $m^3a^{-1}ha^{-1}$ (SE% = 0.4%). Altogether, when accounting for increment, removals, substitutions, etc., the German forests reduce German GHG emissions, in terms of carbon equivalents, by more than 12% (reference year: 2014). They, therefore, play an important role with respect to reducing national greenhouse gas emissions (BAUHUS et al., 2017), and serve in climate change mitigation. Germany opted for the accounting of forest management as a measure of GHG emission reduction according to the Kyoto Protocol.

Between 2002 and 2012, an average of 76 million m^3 per year of raw wood (timber under bark) was harvested in Germany (BMEL 2014). In 2017, net import of round wood was about 5 million m^3, with an import of about 9.1 and an export of about 4.1 million m^3 (Statista, 2019). In terms of value of wood and wood products, Germany is a net exporter with a balance of 6.5 billion Euro

(WEIMAR, 2018). Considering these figures, Germany ranks third in the world, after China and the USA, in terms of value of exports of wood products (BMEL 2018a). While (reference year 2016) the economic cluster of "forest and wood" had a share of 1.8% of the German GDP (STATISTISCHES BUNDESAMT, 2017), the primary production sector of forestry alone had a relatively small share of just 0.1% (Thünen-Institute for International Forestry and Forest Economics 2019) – this figure takes into consideration that GDP is calculated as usual, without considering all the immaterial functions and services of forests.

There are more characteristics of German forests that have relevance for NFI planning and implementation: about 49% of the forest area in Germany is privately owned. There are only few large-area forest owners (with a maximum size of about 20,000 ha), and there are about 2 million forest owners, of which about 25% have forest properties smaller than 20 ha (BMEL, 2014). In the state forests (forests owned by the Federal States or by the Federal Government), which cover about 32.5% of the total forest area, there has been, and continues to be, a long history of mandatory taxations for forest management planning. These are called the "Forsteinrichtung": in intervals of 10 years, forest planning experts visit each stand, make a stand description, assess the implementation of the past management plans, and make suggestions for the next 10-years' planning period. Together with the more recently established forest management inventories, these taxations yielded, and yield, figures about growing stock and growth, which serve as an input for silvicultural planning. Consequently, in the early discussions about a German NFI, many forestry experts and practitioners assumed that high quality information on relevant forest variables from these taxations that occurred all over Germany would be readily available – in this way, a need for an NFI was not recognized by all.

Germany is politically and administratively sub-divided into 16 Federal States. The cities of Berlin, Bremen, and Hamburg are each considered one "City Federal State". Forestry is under the authority and legislation of the Federal States. That means that forest management is governed in each Federal State by its own State Forest Act, which adheres to the Federal Forest Act that: (1) defines the framework regulations at the national level and (2) defines forest-related projects that extend over the whole country. An NFI is a national-level endeavor, whose legal basis needs to be defined and whose implementation needs to be mandated in the Federal Forest Act. The Federal States are obliged to implement this national-level project. Forest area, forest cover percent, and forest types are quite different between the Federal States, making devising a common inventory design a complex discussion and optimization process. For example, according to the estimates from the 3rd German NFI, forest cover ranges from around 11% in the Federal State of Schleswig–Holstein to about 42% in Hesse and Rhineland-Palatinate, average growing stock ranges from 272 m^3ha^{-1} in Saxonia-Anhalt to 396 m^3ha^{-1} in Bavaria, proportion of private forests ranges from 24.5% in Hesse to 66.8% in Northrhine-Westfalia. Also, the forest services are organized differently between the Federal States. Because of the differences between the 16 Federal States, and the fact that responsibilities for forest matters lie within each of these states, the implementation of a forest monitoring system over the entire country is not only a complex technical, but also a lengthy organizational and political challenge: one in which 16 potentially different "viewpoints" need to be discussed, and where compromises need to be found.

3. BRIEF HISTORY OF FOREST ASSESSMENTS ON THE AREA OF TODAY'S GERMANY

We start our historic view in the mid-19th century. Since then, the area of Germany has changed quite considerably (see also SCHMIDT, 1994). Germany lost areas in the east after World War I and II and was divided into the German Democratic Republic (GDR, the Eastern part of Germany) and the Federal Republic of Germany (FRG, The Western part of Germany). Starting in the 19th century, there was an early government interest to assess land use and its distribution. While the main driver for this interest was the agricultural production and food security for an ever-increasing population (VOLGMANN, 1966), forest area and production had also been determined in these assessments. SCHMIDT (1994) analyzed the forest area in Germany over time from a number of sources resulting in the time series presented in *Table 1*. The Federal-level figures before 1987 come from questionnaires about land uses, and not from statistical sampling studies. These agricultural inquiries started in 1878 and, by a decree of the Federal Council of the German Empire (Bundesrat des Kaiserreichs), were institutionalized in 1892 in 10-year cycles (see also POLLEY et al., 2010; in TOMPPO et al., 2010, p223ff and SCHMITZ/BMELV, 2005). Regarding forest, the statistics derived from these inquiries were mainly about forest area, forest type, ownership, and type of management; from 1900 onward, further variables were recorded including age-class and yield of the past 10-years' period (SCHMITZ/BMELV, 2005). That means, from these assessments, one cannot derive figures on growing stock per hectare or increment per hectare. Also, the underlying definition of forest used at the different points in time could not be found in any of the respective statistics, nor were statements found about structure, composition or degradation status. The early questionnaires in the 19th century simultaneously recorded information on the agricultural and forestry land use. VOLGMANN (1966, p. 38f) suspects here an upwards bias for the figures of forest area in the early inquiries because the land tax for agricultural land was much higher than that for forest land. So, farmers might have been tempted to understate the area of their agricultural land while overstating their forest land areas. In 1937 there was the then most comprehensive forest inquiry in the Germany. After World War II, between 1946 and 1950, there were several assessments of forest area and growing stock to generate an overview of the forest production conditions;

these assessments were again based on inquiries and on data from forest management plans. The last comprehensive questionnaire-based assessment of management types and species of forest resources in Germany was implemented in 1961–1962, with reference date 1.10.1960 (for the Federal Republic of Germany only, then). The data was collected in questionnaires from forest owners and forest district offices, analyses were done by the Statistical Offices of the Federal States and the results were published in four volumes by the FEDERAL STATISTICAL OFFICE in 1964 and 1966 (SCHMITZ/BMELV, 2005).

The first large-area inventory of forest growing stock in Germany ("Holzvorratsinventur") that used statistical sampling, was implemented in the German Democratic Republic (GDR, Eastern Germany) in 1956–1957 (RICHTER and GROSSMANN, 1960). It did not cover all forests at the time. However, the experiences from that pilot inventory lead to the establishment of the first statistically designed NFI in Germany (GDR), in the years 1961–1965 (GROSSMANN, 1959). This inventory deserves a closer look, as it was the first large-area forest inventory in Germany that followed the experiences of Nordic countries. It was an outcome of the strategy of GDR to become independent of timber imports and to take stock after a brief period of consolidation after World War II. However, it is hardly mentioned in publications that detail the history of forest monitoring in Germany.

This large-area inventory in GDR was the first one in Germany to explicitly give standard errors of estimation when reporting the results and was the first to emphasize the role of sampling statistics – in particular, regarding the error variance as a guiding factor for planning the inventory design. Also, it was among the first sample-based forest inventories in Germany that had been installed as a permanent inventory following the example of the Nordic countries. Over 5 years, an annual number of 4400 plots (nested circular plots) were recorded: these 4400 plots were distributed over the whole country so that yearly results could be produced, as given in *Table 2*. The organization of field work was spread over a period of 5 years, as only a limited number of field staff were available for this task (GROSSMANN, 1966). This approach may have been a precursor of the modern panel systems for national forest monitoring. However, at the time, a model-based adjustment for the 5 different points in time had not been implemented. The results that were published for growing stock are given in *Table 2*.

The first large-area forest inventory that had a statistical basis in the FRG was implemented in 1970–1971 in the Federal State of Bavaria (total land area about 71,000 km^2). That forest inventory was part of a larger research-oriented project to model the availability of the raw material wood up to the year 2000. A university institute (Institute of Forest Growth/Institut für Waldwachstumskunde) had been contracted to do this study. It was found (KENNEL, 1972; FRANZ, 1975) that the inventory data from the regular taxations for forest management planning were not sufficient, nor suitable as a starting point for such large-area and long-term predictions. This was because (1) such taxations were only available for the State forest, but not for private forests (which hold a share of more than 50 % of the forest area in the Federal State of Bavaria) and (2) measurements were done in these taxations only for older stands that were close to harvesting, and there were no measurements available for smaller dimensions that were required to model longer-term projections of timber production. As a conclusion, the State Forest Service of Bavaria decided to implement a large-area forest inventory. The design planning of this inventory referred explicitly to the experiences from the large-area forest inventory in GDR (FRANZ, 1973). A square grid of 1 km side length was laid out over the territory of the Federal State of Bavaria, and nested circular sample plots were established at all forest grid points. Altogether, a total of n = 21,819 forest plots had been measured (KENNEL, 1972), which allowed for both precise estimations (the

Tab. 1

Forest area percent in Germany (country reference area as of 2018) for the time period from 1834–1989 (from Schmidt 1994). The Figures after 2000 are added from the results of the German NFIs (BWI 2002 and BWI 2012). The figures up to 1981 do not inform about the forest conditions nor do they guarantee that they base consistently upon the same forest definition. FRG = Federal Republic of Germany; GDR = German Democratic Republic.

Waldflächenprozent in Deutschland (bezogen auf die Staatsfläche von 2018) für den Zeitraum von 1834-1989 (aus Schmidt 1994). Die Zahlen nach 2000 sind aus den Ergebnissen von BWI 2002 und BWI 2012 hinzugefügt. Zu den Angaben bis 1981 gibt es weder Daten zu Charakteristika wie Grundfläche und Baumartenzusammensetzung, noch kann nachgewiesen werden, dass die gesamte Zeitreihe auf derselben Waldefinition beruht. FRG = Bundesrepublik Deutschland; GDR = Deutsche Demokratische Republik.

Year	For the area of FRG	For the area of GDR	For the area of entire Germany
1834	25.1%	22.0%	24.2%
1858	26.7%	23.4%	25.7%
1878	27.7%	25.1%	26.9%
1900	28.1%	25.8%	27.4%
1913	28.5%	26.3%	27.8%
1927	28.2%	26.2%	27.6%
1935	27.7%	26.9%	27.4%
1950	27.8%	26.2%	27.3%
1960	28.5%	27.4%	28.2%
1970	28.8%	27.4%	28.3%
1981	29.4%	27.5%	28.8%
1989	29.7%	27.7%	29.1%
2002			31.0%
2012			32.0%

Tab. 2

Growing stock estimated from the large-area forest inventory in the German Democratic Republic (GROSSMANN, 1966).

Vorratsschätzungen aus der forstlichen Großrauminventur in der Deutschen Demokratischen Republik (GROSSMANN, 1966).

Year	Growing stock [m^3ha^{-1}]	SE%
1961	129.20	0.82
1962	130.95	0.98
1963	132.64	1.07
1964	139.37	0.84
1965	133.29	0.82
Total	133.09	0.40

relative standard error, for example, of the estimated forest area was 0.7%), as well as estimates for smaller areas. Regular staff of the forest districts had been selected to perform the field work. The field work was completed, on average, in 4–5 weeks with about 300 different field teams collecting the data. About 6% of the field plots were rechecked; however, the data of this rechecking campaign was never published to the best knowledge of these authors: it is unclear whether the large number of field teams may have caused issues in data quality.

Growing stock was estimated at 292 m^3ha^{-1} (FRANZ, 1973). The official figures of the average growing stock for the whole of the FRG as published, for example, by UN-ECE/FAO (1976, 1986) or referenced by KUUSELA (1994), were at that time less than half of this aforementioned figure. *Table 3* gives a time series of internationally reported figures for growing stock and increment in the Federal Republic of Germany from 1950 onwards. The results of the first German NFI in 1987 confirmed that the stock was about twice as high as previously reported; additionally, the first repeat NFI in 2002 proved this to be about the same for the increment. There is no doubt that forests in Germany were accumulating stock after heavy depletions during and after World War II. During this time, huge masses of wood were extracted for fuel, construction, and reparation payments. However, this alone cannot explain the heavily downward biased reported figures up to the implementation of the country-wide forest inventories in the 1980s.

In retrospect, it can be concluded that the implementation of a national-level permanent forest inventory, consisting of a uniform design and based on principles of statistical sampling, had long been overdue in order to both generate clarity, and to update the rather fragmented and incomplete figures from the earlier decades.

4. THE BEGINNINGS OF THE GERMAN NFI IN THE 1970S/80S – WHY GERMANY WAS SO LATE IN IMPLEMENTING A NATIONAL FOREST INVENTORY BASED ON SAMPLE-BASED FIELD OBSERVATIONS

Currently, in 2019, planning for the 4th German NFI is ongoing and the foreseen reference year will be 2022. As the design of this inventory is based on the NFI in the FRG, the development and history (even though comparably short) of that inventory is outlined here.

In the 1970s, the discussions in FRG intensified about updating large-area forest information from the previous forest inquiry in 1960. This was not only to be better-informed about the production potential of the raw material wood, but also to be better-guided regarding national-level forest-related policies under various changing conditions. Heavy storms in the years 1967, 1972 and 1984 had affected large forest areas, as did snow damages in the winters of 1981 and 1982 (SCHMITZ/BMELV, 2005). Also, starting from the late 1970s, air pollution-induced forest decline dominated forest-related discussions in Europe. As a result, the first country-wide forest condition survey had been rapidly introduced and implemented in 1983 in the FRG, without long preparations of a legal framework. This forest condition survey in Germany was the precursor of the ICP Level 1 inventories that take place all over Europe today.

The early discussion in Germany about establishing an NFI based on statistical sampling had also been triggered by the experiences and the successful implementation of the Bavarian large-area forest inventory and by the publication of the comprehensive new textbook "Forest Inventory" by LOETSCH et al. (1973). On the occasion of the 1974 annual meeting of the Arbeitsgemeinschaft für Forsteinrichtung ("Working group on forest manage-

Tab. 3

Growing stock and net annual increment for the FRG published for the years 1950–1980 from KUUSELA (1994, Tables 3.2 – 3.4, based on FRA 1990 data), and resulting from the German NFIs from 1987 onwards (that is: BWI 2002 and BWI 2012). For the purpose of direct comparison, these figures refer only to the "old" (Western) Federal States. From 2002 onwards, the NFI covers all of reunified Germany. In 2002, the 2nd German NFI allowed the direct estimate of increment for the first time – but only for the Western Federal States [additional data in square brackets for 1960 and 1970 come from UN-ECE 1976 and 1986, and are given here for comparison].

Vorrat und jährlicher Zuwachs in der Bundesrepublik Deutschland für den Zeitraum von 1950–1980 aus KUUSELA (1994, Tabellen 3.2–3.4 basierend auf Daten von FAO FRA 1990), und aus den Bundeswaldinventuren ab 1987 (BWI 2002 und BWI 2012). Um Vergleichbarkeit zu sichern, beziehen sich alle Zahlen nur auf die „alten" (westlichen) Bundesländer. Ab 2002 bezog sich die Bundeswaldinventur auf das wiedervereinigte Deutschland. In 2002 waren somit erstmals Veränderungsanalysen möglich, allerdings zunächst nur für die „alten" Bundesländer. [Zusätzliche Daten in rechteckigen Klammern für 1960 und 1970 stammen aus UN-ECE 1976 und 1986 und sind hier zu Vergleichszwecken wiedergegeben].

	1950	1960	1970	1980	1987 BWI 1	2002 BWI 2	2012 BWI 3
Growing stock m^3ha^{-1}	147.1	144.8 [155.3]	149.5 [144.8]	158.0	298.0	320.0	349.0
Net annual increment $m^3a^{-1}ha^{-1}$	4.2	4.6 [5.6]	5.0 [4.82]	4.9	6.9	12.6	11.5

ment planning") in Lübeck, Prof. W. SCHÖPFER from the Forest Research Institute in Freiburg (FVA Freiburg), made the formal proposal for a nationwide multi-functional large-area forest inventory. After a controversial discussion, this proposal was forwarded to the responsible ministry in Bonn. Eventually, and after lengthy discussions, a working group was established to start planning for design elements of a "country-level forest inventory for FRG". Interestingly, the term "national forest inventory" had been deliberately avoided at the time because the plans referred only to the Western part of the divided nation; instead, the term "Federal Forest Inventory" ("Bundeswaldinventur") was coined. A summary of presentations and discussions of the 1974 meeting in Lübeck is contained in the 1975 special issue of the German forestry journal AFJZ on large-area forest inventories ("Großrauminventuren"). There, HENNE (1975) commented in general terms about the virtues of sample-based forest inventories that rely on scientific approaches and not just on expert assessments both for large-area inventories and for forest management inventories. However, at this meeting of forest taxation experts in 1974, he explained that the concept of a country-level forest inventory had been critically discussed but a state-wise approach favored over a country-level solution. It may be hypothesized that this quite dismissive attitude towards an NFI had also to do with: (1) the fact that within the federal system in Germany, the Federal States are responsible for forestry administration on their territories and hence, the Federal Government has no executive mandate regarding forestry, (2) that an NFI has goals and design characteristics quite different from a smaller-area and state-level forest taxation (possibly not appreciated by the forest taxation experts) and (3) that an independently implemented NFI might have been perceived as criticism to the quality of the data coming from the differently-organized state-wise forest taxations. LOETSCH (1975), an internationally experienced forest inventory expert, discussed and promoted the idea of and a need for a large-area forest inventory for the FRG. The successful implementation of NFIs in Austria (1961–1970) and in Bavaria (1970–1971) were powerful arguments in his favor and were then covered by papers in the 1975 special issue of this journal on large-area forest inventories. Repeated reference was also made to the Swedish NFI; but interestingly, the early experiences from GDR were not referenced in that special issue.

As for the other early forest inventories in Germany (in the GDR in 1961–1965, in Bavaria in 1970–1971), the planning for the first NFI in the FRG was mainly focused on timber supply, even though the potential multipurpose character of the inventory had been spelled out from the very beginning. LOETSCH (1975), for example, explicitly pointed to the potential multi-purpose character of the NFIs in Germany when he predicted

that, in addition to the information on specific forest production issues, there would be an increasing demand for data on other forest functions including environmental protection and recreation.

The aforementioned working group developed step by step technical options for a country-wide forest inventory, and in 1978, an expert group was formally nominated by the Federal Ministry of Agriculture. This expert group was supported by consultants´ reports, in particular by Zöhrer (one of the co-authors of the forest inventory textbook LOETSCH et al. 1973). However, on a political level, it took many years until an agreement on the meaningfulness of a country-wide forest inventory could be reached between the Federal States. Bavaria, having the experiences from the State level inventory of 1970-1971, along with the Northern Federal States supported the plans from the outset, while other forest-rich states, like Baden-Württemberg, Rhineland-Palatinate, and Hesse, strongly argued against an independent federal-level forest inventory. Instead, they favored a "compilation approach", bringing together the readily available data from the forest taxations. The major argument was that a country-level inventory was not necessary and economically not worthwhile because it was assumed that all information would be readily available from the forest taxations at sufficient quality.

Eventually, the arguments in favor of implementing an independent, country-level forest inventory along a uniform inventory design prevailed. This may be attributed to the patiently insisting, consistently efficient and convincingly persuasive political action of a small group of science-oriented forest inventory experts, in particular Prof. SCHÖPFER from the Baden-Württemberg Forest Research Institute. In 1984, ten years after the first systematically organized discussions on the topic, an amendment to the German Federal Forest Act was formulated. This amendment added a new clause §41a that served as the legal basis for the first country-wide forest inventory in the FRG. Without this legal basis, that regulated the Federal States to collaborate on a country-wide issue, a program like a country-level forest monitoring system could not have been implemented. The declared goal was then to generate a general overview (1) of the forest conditions in the country and (2) of the forest production potential. Guiding examples were explicitly mentioned from the State Inventory in Bavaria 1970–1971, the Austrian NFI 1971–1980, the Swedish NFIs 1972–1976 and 1977–1982 and the recently started (1983) Swiss NFI (BRÄNDLI and HÄGELI, 2019). Again, there was no mentioning of the early experiences in the GDR (DEUTSCHER BUNDESTAG, 1983). The inventory was to be implemented with a uniform design over the whole country (which was at that time the FRG). The inventory design was that of a permanent inventory – but it was not clear whether a repetition would be implemented and when. A regular cycle of the inventory had not been defined in §41a of the Federal Forest Act, but the statement formulated that the inventory should be repeated if there emerged the corresponding need. The division of labor between the Federal and the State Governments was defined; the State Forest Services were mandated to collect the data and the Federal institutions coordinated the overall implementation, data management, and analyses.

In the preparation of this amendment of the Federal Forest Law, an expert panel along with forest service representatives from all Federal States discussed, negotiated, and eventually defined the NFI design and its details. This was laid down in 1986 in a statutory regulation to §41a of the Federal Forest Act (BMEL, 1986), which served as a template for the field manual. Its compilation was a lengthy and heavily meticulous process. This was not only because the diverse interests of the Federal States needed to be considered and compromises needed to be found, but also because many technical scientific questions needed to be answered; some of which required the implementation of time-consuming research and development projects. Most of this work was done in the Forest Biometrics Group at the Baden-Württemberg Forest Research Institute in Freiburg under the supervision of Walter Schöpfer. A central topic was the improvement of modelling individual tree volume as a crucial basis for the estimation of growing stock: traditionally, volume of standing trees is estimated by means of volume tables or functions, an approach which provides species-specific individual tree volume based on diameter (dbh, at 1.3 m above ground) and total height. In Germany, volume tables and functions were commonly only valid on a regional scale. In that way, the development of a harmonized volume estimation procedure was considered indispensable; it would allow for unbiased estimates at the national level. It was, therefore, decided to set up a generic volume calculation procedure based on a uniform taper model which accounts for stem-form variability by an additional measurement of an upper diameter. A numerical description of stem-form by a mathematical model satisfies two applications: (1) individual tree volume prediction by integration of the stem curve and (2) assessment of merchantable timber volume by assortments according to grading rules. The biometric research group developed a mathematical framework for a uniform taper model based on splines which allows diameter prediction at any location along the stem of a sample tree (KUBLIN and SCHARNAGL, 1988; KUBLIN, 2003; KUBLIN, 2007; KUBLIN et al., 2008). The model was fitted on a large sample of trees with measured stem profiles provided by several forest research institutes of the Federal States representing the most important tree species and covering different regions of Germany. Altogether about 29,500 sample trees were analyzed.

The taper model was implemented as a function library, included in application programs. It has been used not only to predict individual volume of standing trees, but also to estimate merchantable volume and harvestable assortments as an output of a simulation program which predicts forest development and future timber supply from the NFI data. This model (WEHAM "Waldentwicklungs- und Holzaufkommensmodellierung") was already developed by the Freiburg biomet-

Tab. 4

The four inventory cycles of the German NFI and their coverage (Eastern states, Western states, all Germany). Printed in bold are those results that had been generated for the first time.

Die vier Zyklen der der Bundeswaldinventur und ihre Abdeckung in Ost- und Westdeutschland. Fett gedruckt sind die Ergebnisse, die erstmals geschätzt werden konnten.

Inventory year and period of field measurements	Reference year	Results produced for	
		Former FRG States (Western Germany, around 248,800km²)	**Former GDR States** (Eastern Germany, around 108,300km²)
BWI 1987 1986-1988	1987	**Estimates of status**	n.a.
BWI 2002 2000-2002	2002	Estimates of status **Estimates of changes**	**Estimates of status**
BWI 2012 2011-2012	2012	**Estimates of status** **Estimates of changes**	
BWI 2022 2021-2022	2022	Estimates of status Estimates of changes	

ric research group for the analysis of the NFI in 1987 (BÖSCH, 1995; KÄNDLER and RIEMER, 2017).

Several variables and design elements had been discussed that did not make it into the design of the first country-level forest inventory in the FRG: determination of biomass was dismissed as biomass models were not available at the time. A precursor of the assessment of deadwood had also been discussed in order to estimate the volume of the logging residues – but eventually was not implemented. The recording of soil variables was dismissed for reasons of costs and logistics, as was the recording of stumps for reasons of uncertainties in determining the age of a stump when it is older than a few years. Increment boring was also not included, in order to not cause damages on sample trees that needed to be periodically remeasured. The integration of remote sensing into the estimation process – aerial photographs at that time had been discussed but was eventually dismissed because uniform imagery was not available all over the country. It was not seen that the necessary investment into the remote sensing components (flight campaign, image pre-processing, and processing) would have led to a higher cost efficiency in generating the information as mandated by the Federal Forest Act.

Several European NFIs had been visited and consulted during the planning phase. At the time, cluster sampling had proven efficient for large-area forest inventory in many countries. The cluster-plot design was adopted also for FRG. Following the terminology used in the Nordic European countries, the clusters were called tracts ("Trakte"). Suitable shape and size of the cluster plots were determined in simulation studies at the Baden-Württemberg Forest Research Institute: square cluster plots of 150 m side length with four sub-plots were favored; this guaranteed that at least one cluster plot could be recorded on one workday per field team. The size of the systematic sample grid originated both from considerations of precision of estimation and from considerations of cost: a 4 km grid size was found suitable as ZÖHRER et al. (1983) reported in an unpublished consultant's report.

While there was still a major focus on the productive function of the forests, the general attitude of the planners was to establish a potentially multifunctional large-area forest inventory.

The basic design of the German NFI is detailed in the next section. Following that, the modifications to the NFI over time, in terms of both the design and the goals, are presented. It should be noted that the NFI planners needed to cope with these modifications as new information arose. *Table 4* lists the three completed and the fourth pending inventory cycle.

5. DESIGN OF THE GERMAN NFI

The basic design of the German NFI follows well-proven design elements of large-area forest monitoring. It was the outcome of intensive discussions and planning where the specific and variable forest conditions and interests of all 16 Federal States needed to be taken into account. The inventory was designed as a permanent inventory with a systematic sampling design on a square grid and a plot design of complex cluster plots as illustrated in *Figure 1* (BMEL, 2014). The systematic grid has a base size of 4 km over the whole country; it was defined with a North-South orientation and was deliberately shifted such that it did not coincide with the grid for the independently implemented forest condition survey. Some Federal States responsible for data collection established denser grids, so that both doubling (2.83 km

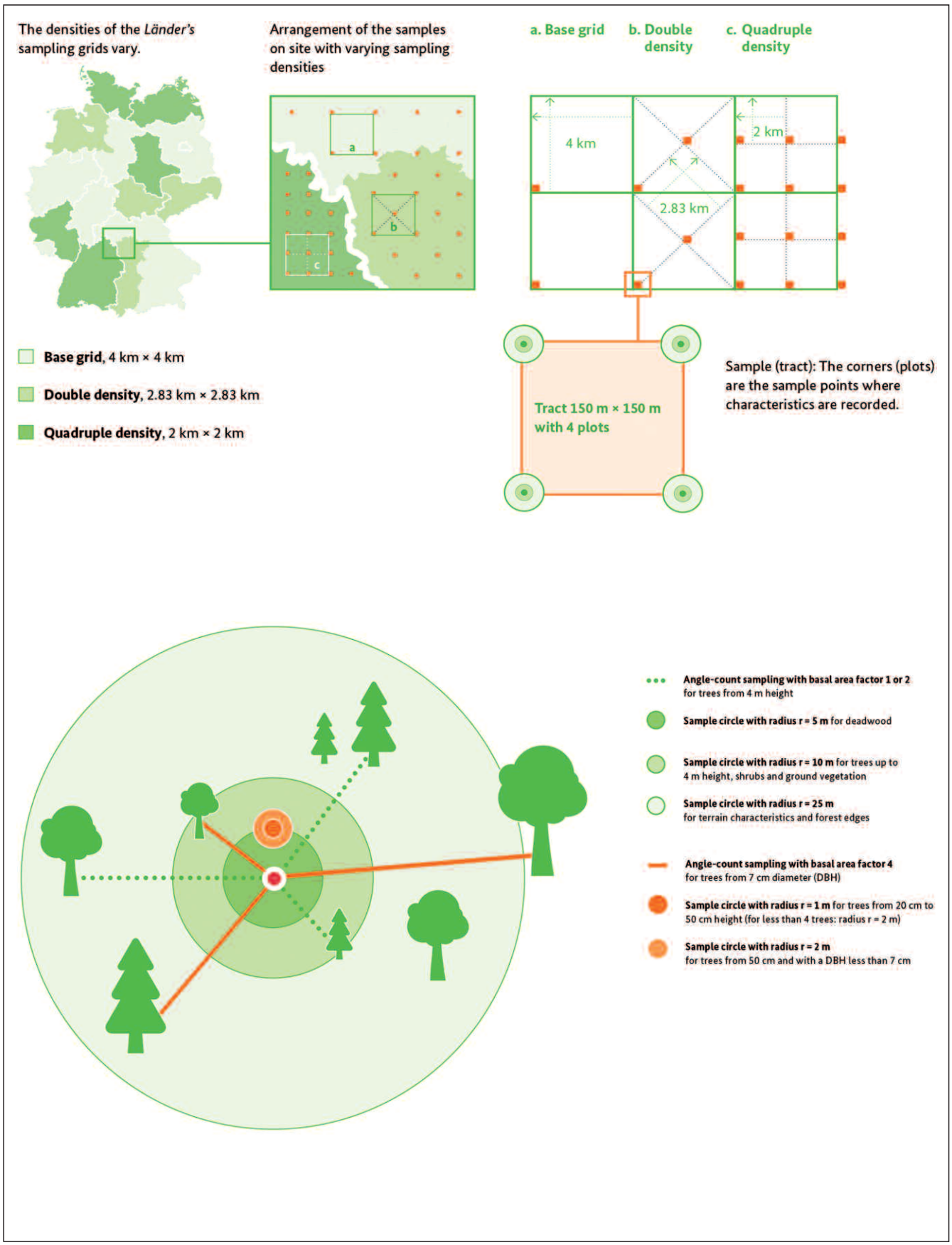

Fig. 1
Sampling and plot design of the German NFI (from BMEL 2014 for BWI 2012). Länder = Federal States.
Stichproben- und Probeflächendesign der Bundeswaldinventur (aus BMEL 2014 für die BWI 2012).

grid) and quadrupling (2 km grid) of sample size was done on about 25% of the national area for both methods (SCHMITZ et al., 2006). This allowed for higher precision of estimation. Estimation of variances and precision were done with the estimator framework for simple random sampling, with the well-known consequence that the calculated standard errors overestimate the true standard errors by an unknown extent. The square cluster plot has a side length of 150 m. At each of the four corner points, nested circular sub-plots of 5 different radii and Bitterlich sub-plots of 2 different basal area factors are established to record the set of inventory variables regarding trees, stand structure, and site characteristics. The 150 m connecting lines between the sub-plots were used for line sampling in the first NFI, in order to estimate the area of forest types (line intercept sampling) and the length of the road network (line intersect sampling) (MATÉRN, 1964).

A sample point was field measured if at least one of the cluster corners (that is: the center of at least one sub-plot) came to lie in forest land. The decision whether a cluster of sub-plots is partly in forest or not was supported by analysis of remote sensing imagery.

Table 5 gives an idea of the size of this inventory program. In BWI 2012, for example, this large sample size allowed for the production of precise estimates for the whole of Germany, where the core variables forest area, growing stock, and mean annual increment were estimated with relative standard errors of 0.7%, 0.4% and 0.4%, respectively (BWI, 2012). For smaller units of reference, precision goes down according to the respective sample size. For example, forest area and growing stock in the relatively large Federal State of Baden-Württemberg was estimated with relative standard errors of 1.2% and 0.7%, respectively. In this case, these results are also due to the densified 2 km grid and the resulting high sample size of n = 4620 clusters. While, for the combined City Federal States of Hamburg and Bremen with a sample size of just n = 15 clusters, the relative standard errors for forest area and growing stock were 25.8% and 12.4%, respectively. Altogether, more than 150 variables were recorded per sample location allowing for a wealth of different analyses.

The development of the German NFI and adjustments to its design and its mandate in its relatively short history of about 3 decades will be described in the next section.

6. ADAPTATION OF THE GOALS AND DESIGN FROM NFI 1 TO NFI 4 IN REACTION TO EMERGING NEEDS AND CHANGING DEMANDS

There were essentially two major events that among other considerations co-determined the NFI planning after the first country-wide forest inventory in the FRG: (1) the reunification and (2) the UNCED conference of 1992 in Rio. The reunification made it necessary to plan for a design for all Federal States. In addition, §41a in the National Forest Act stipulated that the NFI shall be carried out for the whole of Germany – and this reference area had just changed in 1990. The UNCED conference of 1992 in Rio is where the international conventions on climate change (UNFCCC), biodiversity (UN-CBD) and desertification (UN-CDD) were negotiated, formulated, and to which many countries (including Germany) became signatory states. By signing these conventions, the signatory states committed themselves – among various other commitments – to report on the status of the forests on a regular basis.

The second German NFI (= BWI, 2002) was actually the first NFI for the whole of reunified Germany that followed a uniform design. It was planned such that forest-related reporting commitments originating from the international conventions could be served as comprehensively as possible. But, implementation of the second German NFI was not without its problems, even though the results of the first NFI, generated from a uniform and science-based inventory design, had impressively shown how important this independently collected data was. Intensive discussions took place between the Federal States. They discussed whether there was really a "need" for a repetition according to what the Federal Forest Act stipulated; and it was not clear whether a repetition within a reasonable time frame would materialize (SCHÖPFER, 1995). These discussions delayed the implementation of the second NFI so that the plans for its implementation in 1997 and in 2000 did not materialize. Eventually, the second NFI was implemented in 2002, that is: 15 years after the first.

During those 15 years, the recognition of forests and their many benefits and functions for people, for the environment, and for ecosystems was constantly growing and forests were back on the international agenda relatively prominently. This can also be seen from the prominent references to forests and their roles at the UNCED of 1992. Driven by international reporting obligations, and also by a growing interest in reliable forest-related data at the national level, there was a need to amend the Federal Forest Act. In 2010 – during the planning period for the third German NFI (= BWI 2012) important new features were introduced that consolidated and expanded the mandate of the German NFI. At this point, the level of information, the detail, the adequate presentation, and the dissemination of the results of the first two German NFIs were convincing enough to not generate significant opposition. Instead, the planning focused on enhancing and strengthening the NFI as a long-term program. There were intensive discussions about various details of broadening the scope and mandate of the third NFI by various interested parties (NIEBUHR, 2018).

The major technical and organizational developments of the German NFI program over the past 3-4 decades were also reflected in the amendment of the Federal Forest Act in 2010, and are addressed in what follows:

6.1 A permanent monitoring program

One of the most relevant points in the 2010 amendment to the Federal Forest Act was the establishing of

the NFI as a permanent National Forest Monitoring Program: a cycle of 10 years was define.

6.2 Few adjustments of the inventory design

The basic design has not been changed during the NFI's 4 cycles. The sampling design with the 4 km base grid has remained unchanged. But, an increasing number of Federal states made the decision to densify this base grid on their territory (*Figure 2*), so that the total number of forest clusters increased from BWI 2002 (which was the first NFI for the re-unified Germany) to BWI 2012 (SCHMITZ et al., 2006; RIEDEL et al., 2017). The numbers of sampling units are given in *Table 5* for comparison. To get the data and results faster, more inventory teams were employed.

6.3 Adaptations of plot design

A few adaptations were done regarding plot design, both accommodating new variables (see below) and discontinuing design elements that were either not needed anymore or that turned out to be inefficient: the latter refers, for example, to the line intercept sampling for

Tab. 5

Number of sampling units per inventory. BWI = National Forest Inventory (Bundeswaldinventur). IS = Inventory Study, CI = Carbon Inventory. IS and CI are intermediate inventories on a reduced grid in order to produce updated information for UN-FCCC reporting. The drastically increased number of sampling units between BWI 1987 and BWI 2002 results from the German reunification; the increasing number between BWI 2002 and BWI 2012 is mainly because of more Federal States implementing denser sample grids and – to a lesser extent – because of increasing forest area.

Tabelle 5. Anzahl Stichprobeneinheiten. BWI = Bundeswaldinventur; IS = Inventurstudie; CI = Kohlenstoffinventur. IS und CI sind Zwischeninventuren auf einem weiteren Netz, die speziell einer aktuellen UN-FCCC-Berichterstattung dienen. Die deutlich erhöhten Anzahlen an Stichprobeneinheiten von BWI 2002 nach BWI 2012 sind vor allem darin begründet, dass zahlreiche Bundesstaaten ihre Netze verdichtet haben und – in deutlich geringerem Maße – mit einer Zunahme der Waldfläche.

	BWI 1987	BWI 2002	IS 2008	BWI 2012	CI 2017
Over the entire inventory area (forest and non-forest)					
Clusters	28,932	45,204	5,620	49,195	12,074
Subplots	115,306	179,761	22,365	195,630	48,031
Forest					
Clusters with at least one corner in forest	12,391	19,479	2,456	21,144	4,864
Subplots in forest over all clusters	34,951	55,266	7,028	59,903	13,724

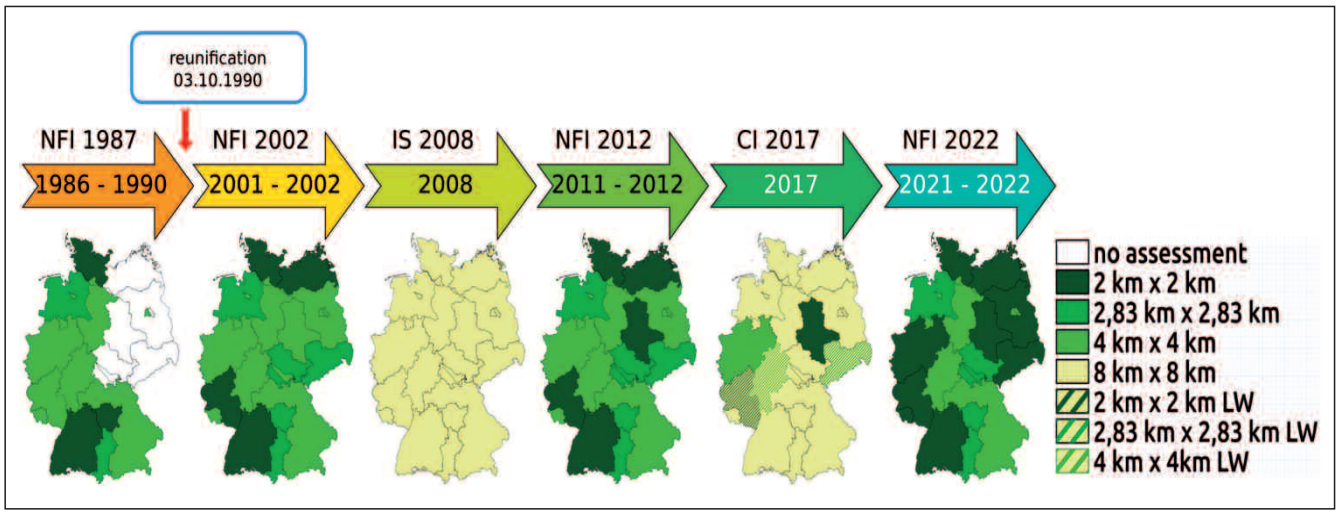

Fig. 2

Development of sampling densities within the Federal States over time. LW = Landeswald = public forest).

Entwicklung der Dichte der systematischen Stichprobennetze in den einzelnen Bundesländern. LW = Landeswald.

estimation of the area of forest types. This was done in the first NFI on the sample lines connecting the four subplots on the 150 m square cluster. It was found, however, that estimating areas of forest types is more efficient when just analyzing the observations at the corner points of each cluster. A theoretical background for this somehow counterintuitive fact is in KLEINN (1994a,b). In the first NFI, the 600m line connecting the cluster corners had also been used to estimate the lengths of forest roads using MATÉRN's (1964) approach of line intersect sampling. This was abandoned because the density of roads in German forests are not being further developed and major changes to road density are not expected. Also, in NFI 1987, the minimum dbh for the sample trees mapped for repeat measurements was set to 10cm, in order to adhere to international standards. This threshold was redefined to 7 cm in the following BWIs, in order to follow German standards. The time-consuming measurements of upper stem diameters at trees with dbh > 20 cm in NFI 1987 served to refine taper models and to more accurately model tree volume. These measurements were only implemented in NFI 2002 in the Eastern Federal States, where the inventory design was implemented for the first time after reunification, on one subplot per cluster (at the South-Western cluster corner). The measurement of upper diameters was then repeated in the Inventory Study 2008 and in BWI 2012, except for the Federal States of Lower Saxony and Brandenburgia. However, measurements of upper diameters will be entirely suspended in the fourth NFI (BWI 2012) because average stem forms depending on species, dbh and height (modelled from upper-diameter measurements of the 3rd NFI) will now be used for the estimation of tree volume and above-ground biomass. This simplification contributed reducing the costs of field work.

The efficiency of the relatively spatially compact square cluster of 150 m had been evaluated by preliminary NFI internal analyses of the intra-cluster correlation coefficient (ICC) for different variables. Over all the forest clusters, the ICC for total growing stock was 0.25469 and was 0.07232 for dead wood stocks. These relatively low ICC values point to a good statistical efficiency of the cluster plot design for these two variables.

6.4 Integrating new target objects and variables, expanding the scope of the NFI

The starting point for the German NFI in the 1970s and 1980s was oriented towards forest resource questions. However, there has emerged an increasing demand for environmental, ecological, and natural conservation information on forests in Germany. There are various environmental monitoring systems of forests in place in Germany. These include the National Forest Soil Survey and the Forest Condition Survey. The forest soil survey was carried out in 1986–1993 for the first cycle and in 2006–2010 for a second cycle (WELLBROCK et al., 2016). The Forest Condition Survey was carried out in 1982 for the first time during the period of acid rain and forest decline (Anonymous, 1983) and is being done and reported annually since then. However, the German NFI has the densest network of sample plots. So, it has a certain logic to enhance the NFI towards a more detailed assessment, including forest ecosystem functions. The 2010 amendment of the Federal Forest Act explicitly demands that the German NFI shall support information generation on nature and landscape as required by §6 of the Federal Law on Nature Protection. By this, the NFI has explicitly been further developed towards a more comprehensive forest ecological assessment program. While various relevant results on the ecosystem forest can directly be derived from standard forest resource inventory variables (like species composition, biomass, biomass distribution, etc.), special indicator systems needed to be developed for other variables like "naturalness of species composition" and "conservation status of protected areas". The orientation towards more ecologically meaningful variables had already taken place between BWI 1987 and BWI 2002, when more detailed variables on forest stand structure, shrub layer, and ground vegetation were integrated, as well as variables on dead wood and important habitats.

Integrating these new variables required adjustments of the plot design (like additional nested sub-plots for the recording of dead wood), and enhancements of the analysis design (e.g. for the estimation of biomass and carbon and for the evaluation of "closeness to nature").

6.5 Integration of remote sensing

Integration of remote sensing had been discussed intensively from the outset: LOETSCH (1975) discussed 2-phase sampling with aerial photographs in the first phase either with a wall-to-wall coverage or strip coverage. RHODY (1986) also presented and suggested a multiphase approach using satellite imagery and aerial photography.

Various studies on the application of remote sensing in the estimation process have been carried out, including a comprehensive study on the State Forest Inventory in the Federal State of Northrhine-Westfalia between 1995 and 1997. There, the recently developed kNN technique had been tested which had previously be successfully applied in the Finnish NFI (TOMPPO 1990a, b). This study in the State of Northrhine-Westfalia, however, identified a series of issues that could occur during implementation in highly structured temperate mixed forests (HÄGGBLOM et al., 1997; TOMPPO and PEKKARINAN, 1997) that would have required comprehensive further research before application. At a workshop in Horn-Bad Meinberg in 1996, the challenges and possibilities of remote sensing integration into the state forest inventory had been discussed. At the time, it could not be concluded that the remote sensing supported kNN approach would make the German national level forest inventory more cost-efficient with respect to achieving the legally defined goals of the BWI. Consequently, the BWI did not adopt this approach and continued as a terrestrial inventory. In the preparation for BWI 2012, the topic had been researched again, given the rapid technical progress in remote sensing technology and image processing. Integration of remote sensing data into the esti-

mation process as practiced, for example, in the Nordic countries is not done in the German NFI as of yet. Currently, remote sensing (available airborne orthophotos) is used by default only for the decision whether a cluster plot is a "forest plot" that needs to be field visited or not. By that, also new forest cluster plots are identified. In cases when it is unclear whether the cluster plot is really a forest plot or not, validation field visits are done.

6.6 Devices for measurements

Usage of mensuration devices also followed the technical development. In BWI 1987, simple mechanical devices prevailed, including data recording on paper forms (except for ultrasonic distance measurements). In BWI 2002 electronic devices were used for distance and height measurements and for navigation. In BWI 2012 there was no longer any prescription of specific devices in the field manual, except for the measurement of dbh by tape. As most of the work was done by forest entrepreneurs hired by calls for tenders, the work had to be defined functionally and not by prescribing devices. Quality and consistency of measurements were evaluated during the regular check cruising.

Some Federal States used their own personnel, but most contracted inventory consultants for field work. Some Federal States made all measurement devices available, while others expected the consultants to bring their own devices.

Navigation is an important component of field work. In BWI 1987, the plot positions were defined, traditionally by locating the track on the map and navigating with a compass and distance measurements. The dense forest road network and availability of accurate topographic maps facilitated such traditional navigation. Experiences with GPS in BWI 2002 did not go smoothly, as position accuracy with the civilian receivers was low, in particular below the canopy. At that time, GPS was the only reliably-working global navigation system and the so-called "selective availability" (artificial blurring of the signal in order to deteriorate the accuracy) was only lifted by the US American president in May 2000, which was in the midst of the preparation phase of BWI 2002. Of course, from BWI 2012 onwards – and already in the intermediate Inventory Study IS 2008, the considerably improved GNSS receivers have become standard for navigation to the plots and for accurate position determination.

6.7 Data recording, management and analyses

Following the development of information technology, significant adaptations took place in data recording and data management. In BWI 1987, data was recorded on paper form sheets and subsequently centrally digitized. Mobile data loggers with an individual software solution and data transfer by CD came into use in BWI 2002. From BWI 2012 onwards, data was transferred and synchronized via mobile phone network or WiFi. A single, central database and centralized data management had to be built up. Field teams downloaded the data prior to going to the next cluster. Only part of the data is visible for the field crew, other parts are used for plausibility checks in the field by the software. All software for field data collection had been developed by the Federal Inventory Administration.

Analyses in BWI 1987 followed a fixed pattern and standard results were produced for Federal-Level and State-Level. Because of the wider range of variables recorded and because of the increased general interest, the analyses became more diverse from BWI 2002 onwards: results were made available online and individual online analyses became possible by interested users based on the preprocessed results. As described below in "An open data policy", raw data are publicly available except for the exact coordinates.

6.8 Quality assurance

Field work in the German NFI is organized and funded by the Federal States. About 60 field teams were deployed in NFI 2012. In NFI 2022 there will likely be about 100 field teams. All field teams are trained in tailor-made training sessions. As a measure of quality control, a percentage of 5% of clusters are checked at minimum, which are rechecked by an independent supervision team since BWI 1987. Federal States are responsible and pursue their own strategy and implement checks partly as "hot checks", where the supervision teams accompany the field teams, and as "cold checks", where the clusters are checked after completion of all respective cluster measurements, within a time period of 2 weeks.

Electronic data recording in the field, and availability of the prior measurements, allowed for immediate plausibility checks and reduced the chance of typing and data transfer errors. Analyses were carried out independently in two institutions (the Federal Research Institute – Thünen Institute – and the Baden-Württemberg Forest Research Institute) so that errors of implementing the algorithms could rapidly be identified.

6.9 Important data source for reporting to international processes

German NFI data has become an important input for reporting to international processes. This includes MCPFE (the Ministerial Conference for the Protection of Forests in Europe), the Climate Convention UN-FCCC, the Kyoto Protocol, and the Biodiversity Convention UN-CBD (Bolte et al., 2008). The detailed reporting obligations to the Kyoto Protocol result from Germany's choice to also include "Forest Management" in the forest carbon accounting. The corresponding first commitment period for the Kyoto Protocol was 2008–2012. The end point of this commitment was in 2012, which coincided with Germany's third NFI. However, the data from the second NFI (reference year 2002) was considered outdated as a reference for the start of the first commitment period. So, an extra carbon inventory (inventory study = "Inventurstudie") was implemented in 2008 to generate an up-to-date database for the start of the first commitment period, as required when applying the stock-change method for the assessment of forest carbon emis-

sions. A second carbon inventory took place in 2017, but not at the end of the second Kyoto period in 2020. A separate carbon inventory in 2020 would have been too close to the next regular NFI assessments (=BWI 2022) in 2021 and 2022. This decision is supported by the IPCC KP supplement 2013, section 2.3.4 and by the IPCC 2006 (Volume 1, chapter 5, section 5.5.1). Both references define a 5-year cycle as sufficient for a consistent time series. In addition, intermediate information about the development of forests, growth, and utilization is of high interest for decision makers in politics, enterprises, and NGOs. These intermediate inventories sample an 8 km subset from the base grid of 4 km. Organization, funding, and implementation for the Inventory Study 2008 was fully done by the Federal Government, without involvement of the Federal States. And, the same 8 km grid was used all over Germany, without regional densifications in Federal States (except for one State where a posterior densification was done). Eventually, about 12% of the NFI points were observed for these carbon inventories (POLLEY and BOLTE, 2010; SCHWITZGEBEL et al., 2009). In the second intermediate inventory, the Carbon Inventory 2017, several Federal States decided to seize the chance, and made additional measurements on a denser grid. Some Federal States expanded this CI 2017 to a full-blown state-level Forest Inventory supporting the Federal coordination team with the implementation. Since the 2010 amendment of the Federal Forest Act, these intermediate carbon inventories had a legal basis. They follow the design of the NFI, but only those variables that are needed to estimate the development of above and below ground living biomass and dead wood, those variables relevant for estimating forest carbon emissions, are being recorded. To that end, biomass functions had to be developed, which was done by the Baden-Württemberg Forest Research Institute under a contract with the German Federal Ministry of Agriculture (RIEDEL and KÄNDLER, 2017; VONDERACH et al., 2018). By introducing the intermediate carbon inventories, a 5-year cycle of estimating core forest variables had been established since BWI 2002.

6.10 Reporting and communication

The results of BWI 1987 had been published at the federal level in 1992 as two volumes of hardcopies. The first and shorter volume (BMELF, no date, a) had a methodological overview, a compact description of results and about 60 basic tables. The second volume (BMELF, no date, b) was a more comprehensive collection of tables. These collections of tables had also been printed for each of the Federal States. Altogether, a total of about 3,500 pages of tables had been printed. It was only two years later that the Federal Ministry published an evaluation of the results with conclusions for forest policy purposes in a separate brochure (BMELF, no date, c). BWI 1987 was implemented before the German reunification, so the results only covered the Western Federal States. After reunification, of course, there was an interest in having comparable data for the new Federal States; this data was published in 1994 (BMELF, no date, d) and was produced from an evaluation of forest planning data that was available in Eastern Germany. In 1996, model results were published for the raw wood potential in forests and was projected until 2020. This included a detailed report from the responsible Federal Research Institute (POLLEY et al., 1996a) as well as an overview brochure from the Federal Ministry (POLLEY et al., 1996b). Because all these early reports were written before the Internet became widely established, they were only printed and do not exist online. All reports were only published in German.

For BWI 2002, the communication strategy had been further developed. Again, an overview brochure was published with explanations of the main results on the federal level and a short historical and methodological chapter (SCHMITZ et al., 2004). Later, comprehensive sets of tables were published also giving some results for the Federal States (POLLEY et al., 2006). An extra report elaborated on methodological details of the inventory design and the analyses (SCHMITZ et al., 2006). Similar to the BWI 1987 inventory results, the raw wood potential of the four coming decades (from 2003 until 2042) was described in an overview brochure and a larger volume of tables. (SCHMITZ et al., 2005b). The corresponding forest development projection and some maps of the distribution of natural forest communities and their trees species were published in a special report (SCHMITZ et al., 2005a). Then, most reports were published not only in German, but also in English. Unlike the BWI 1987, the Federal Ministry did not print any reports for the Federal States because all data was now available on the Internet. Additionally, most of the Federal States published their own inventory reports based on this data. Many more results than in the printed reports were published on the Internet at www.bundeswald-inventur.de. In addition, DVDs with result databases for the inventory and for timber supply modelling were produced.

Starting with BWI 2012, online publication of the detailed results and tables became standard. As in former inventories, a brochure had been printed as a core information source for the wider public (SCHMITZ et al., 2014). Besides other topics, this brochure had a special focus on ecological topics that were and are being publicly discussed in Germany. For the more specifically interested audience, three publications were issued: (1) results tables (SCHMITZ et al., 2016), (2) a report on the modelling studies of forest development and raw wood potential (ROCK et al., 2016; SCHMITZ et al., 2017) and (3) a description of the inventory methods (RIEDEL et al., 2017). All these reports are available online (www.bundeswaldinventur.de) and most information is also available in English. In addition, most Federal States produced their own inventory reports. The BWI user interface (now at https://bwi.info) was improved, maps and graphs were added, and the original data can now be downloaded. News is currently communicated via Twitter (https://twitter.com/bwi_info).

When comparing the BWI publication strategies from BWI 1987 to BWI 2012, the following developments can be seen: (1) Results are increasingly presented in a targeted, group-oriented manner for decision-makers, media and the interested general public. (2) Ecological topics became more important and are now being explicitly addressed. (3) The potentials of the Internet are more frequently used for the presentation of the various large data sets. (4) Hardcopies continue to be considered an important medium for public relations work and for long-term archiving.

6.11 Modelling of scenarios of forest development

An important national program that builds directly on the German NFI and its results has been established after the first NFI (=BWI 1987) in 1996: modelling timber supply prospects ("Holzaufkommensmodellierung"). Later, these studies were expanded to modelling both forest development and timber supply prospects, generating science-based scenarios both for the ecosystem forest and the resource forest, called WEHAM ("Waldentwicklungs- und Holzaufkommensmodellierung"). Currently, it is in use for the time period from 2013 to 2052 (BMEL, 2014). While these model predictions are important for the Kyoto reporting at the forest management reference level, for the wood industry, and for the formulation of forest related policies, the scenarios are also being evaluated, for example, with respect to biodiversity issues (REISE et al., 2017).

6.12 International networking and harmonization

Since its foundation in 2003, the German NFI has been member of ENFIN, the European National Forest Inventory Network, and actively participates in its networking activities. ENFIN initiated the two cost actions E43 "Harmonisation of National Forest Inventories in Europe: Techniques for Common Reporting" and FP1001 "Improving Data and Information on the Potential Supply of Wood Resources: A European Approach from Multisource National Forest Inventories (USEWOOD)" on standardization and harmonization of national forest monitoring in Europe. They considerably contributed not only to harmonization of definitions and approaches, but also to international networking and exchanges (TOMPPO et al., 2010; BARREIRO et al., 2017). The conversion of the national results into the formats for international reporting was significantly facilitated through these intensive efforts of harmonizing approaches and definitions. However, there were no immediate modifications or adaptations of definitions used in the German NFIs.

6.13 Costs

Total cost of the BWI 2012 were about 21 Mio Euro of which about 15 Mio Euro were borne by the Federal States and about 6 Mio Euro were provided by the Federal Government. Costs for field work remained quite constant over the NFI cycles. This is also because the guideline for planning is that the inflation-adjusted costs for field work (to be covered by the Federal States) should not increase. However, because of the growing responsibilities in analysis and reporting, the core NFI team, funded by the Federal Government, has grown from 2 staff members to 7 staff members from BWI 1987 to today.

6.14 An open data policy

German NFI data is being collected and analyzed with tax money so there is a general obligation to also make the data publicly available. While there was not much explicit public interest after BWI 1987, the NFI data and the results' of analyses can now be found on online platforms. The online portal https://bwi.info (also available in English) allows for both the retrieval of standard results tables and also the flexibly to build individualized tables and data sets from a multitude of combinations of variables for defined regions of interest from the data of BWI 2012. Many of the statistics listed in this article were retrieved directly from this online platform. For geographically explicit analyses, the NFI team at the Thünen Institut needs to be commissioned, but only if such analyses are compatible with privacy regulations.

6.15 Increasing utilization of NFI data and results in research and in the general public

The open data policy, the easy availability of the German NFI data, and the intensive publication strategy of the Federal and State institutes involved in the NFI implementation may be among the reasons that have led to increased use of NFI data for special analyses, both in research and in the general public. Also, after the third cycle of the NFI, change estimates for the whole of Germany are available for the first time (see also *Table 4*), which has made the NFI data sets even more interesting. The results of the BWI 1987 were mainly further analyzed in scientific studies and in research for optimization of the inventory design; they were hardly taken up by the general public or by NGOs. This has changed significantly, and BWI data is now often used for scientific studies (e.g. STAUPENDAHL and SCHMIDT, 2016 to derive growth models; KLEINN et al., 2011 to estimate scale-dependent forest edge lengths) and also in discussions about status and development of forests and forestry in Germany (e.g. ENGEL et al., 2016 on the political goal to have 5 % of all forest area in German without management for timber).

In a research project funded by the federal "Forest Climate Fund" ("Waldklimafonds"), the German NFI was extended to include a soil and climate dataset (a so-called "environmental vector") which were assigned to the sample plots of the basic 4 by 4 km grid. The environmental data was elaborated in a joint research approach by experts from Federal States, forest research institutes, and Hamburg University to generate harmonized and uniform data based on regionalization methods (DIETRICH et al., 2019). The extension of the NFI with the environmental vector is aimed at improving the estimation of site suitability and productivity of the forests under the present and future climate. In combination with forest growth models, it is possible to assess

the future development of the forests of Germany, including their potential raw timber stocks and carbon storage potential, based on NFI data.

7. OUTLOOK

It is likely that forest-related data will continue to be in high demand in Germany in a number of contexts both regarding the production function of the resource forest and the conservation function of the ecosystem forest and NFI data will continue to play a central role here as a reliable source of quality-checked science-based data. One important context is climate change: forests offer an efficient low-cost contribution to reducing carbon emissions and a number of positive side-effects come along with sustainable forest management and the substitution of wood for other raw materials. Also, it is likely that the time series and site-specific NFI data will become more and more valuable for generating and validating scenarios of future forest development, including production of raw material, species selection, forest structure, and definition of rotation periods. In this context, conservation of forests and their diverse structure is one goal, but the forest stability and mitigation of the effects of catastrophic events is another: it is expected that the frequency of heavy storm events, draught events and forest fires will increase in Central Europe.

In the following, we discuss some points of current discussion which are in part not yet taken up in the upcoming BWI 2022.

7.1 Sampling Design

The systematic design on a square grid has proven efficient and allows flexible adjustments of sample sizes within Federal States, if needed. Accordingly, the number of sampling units has constantly increased from inventory to inventory, as more and more Federal States used denser grids to produce more precise estimates (see also *Table 5* and *Figure 2*). With the intermediate carbon inventories, the legally defined 10-year cycle has effectively become a 5-year cycle since 2002, responding well to the needs of updated information. While various countries have switched to a panel-system in which data collection and analyses are done on a yearly basis completing a full cycle every 5 or 10 years, the German NFI will remain a periodic one. This is also for political and constitutional reasons: the federal system in Germany gives authority for forest management to the Federal States and the Federal Government must not engage in permanent tasks in this domain. However, a panel system with field work all year round would be such a permanent task.

7.2 Small area estimation

The typical units of reporting for a national forest inventory are the entire country and the individual Federal States. The smaller these reporting units, the smaller the sample size, and the less reliable the estimates. For many decades, however, there have been discussions in the NFI community on how to also produce information for smaller areas. Among the first was the Finnish NFI, where TOMPPO (1990a,b) applied his kNN approach linking NFI data to remote sensing data in order to produce maps of growing stock over the whole country at high spatial resolution. Corresponding research is also ongoing for the German NFI. However, privacy is an issue: it has always been emphasized that the NFI sampling grid is too coarse to produce results for smaller areas, like a single forest enterprise. A successful application of small-area statistics will certainly cause further discussions.

7.3 Additional variables/topics

In most countries, NFIs are the most comprehensive (frequently the only) inventory system for renewable natural resources and ecosystems; of course, with a focus on forests. The systematic sample over the entire country lends itself to continue integrating further variables as a function of emerging forest-related issues. Such integration, of course, needs to be economically feasible: the forest inventory field teams must be able to acquire the necessary knowledge in their regular training sessions and the field measurements must not be too time consuming.

The integration of biodiversity variables into the German NFI are currently being discussed. This means not only a more detailed assessment of vegetation diversity, but also a more detailed assessment of tree genetic diversity. Compared to other taxa, trees have a relatively high genetic variability. The understanding of this variability is also important in the context of the adaptation potential to changing environmental conditions, including climate change. The trees' genome assessment is particularly relevant, as in former times seed sources from distant sites had been used for plantings (FUSSI et al., 2013; KOSKELA et al., 2014; KRABEL et al., 2010). By that, stands had been established that were possibly not adapted to current and predicted site conditions. Of course, the contrary is also possible: in that case, the seed transfer had been very advantageous and successful and the site conditions in the region of origin match with the predicted future conditions. The goal is to characterize tree genetic variability, to identify priority areas for genetic conservation, to assess local adaptation to biotic and abiotic stresses, and to identify promising provenance regions for seeds.

The German NFI is planned to become the data source for such genome information: on a subset of about 4000 sample positions, a number of about 20000 samples of leaves, needles, buds, and small twigs will be taken from the six most important tree species: Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), beech (*Fagus sylvatica* L.), oak (*Quercus petraea* (Matt.) and *Quercus robur* L.), Douglas fir (*Pseudotsuga menziesii*), and white fir (*Abies alba*). The samples will be conserved until genetic analyses by DNA-chips will be economically feasible.

7.4 Integration with other national level assessments

While the German NFI focuses on the resource and ecosystem forest, there are two more national-level assessments on forests: the forest soil survey and the forest condition survey. Both take place on a different sample grid than the NFI, in different time intervals, and are managed by specialized groups. The forest condition survey had its start on the federal level in the period of "forest decline" in the early 1980s and is since then repeated on a yearly basis along a European standard. The forest soil survey took place in 1986 to 1993 and was repeated once in 2006–2008 and the third is planned for 2022–2024. In most Federal States, the soil survey uses the same sample grid as the forest condition survey. Discussions to use the same sampling grid for all these three national-level surveys have taken place various times, but so far, these projects remain individual in most Federal States, though closely coordinated: the expected losses because of the differences in approaches and history (time series) are valued higher than the potential synergies.

7.5 Systematic impact analyses

It is one of the interesting features of national forest inventories worldwide that there is much research on statistical and technical questions, and that the approaches become more and more efficient and gradually more precise. A lot of efforts are typically invested into preparation and implementation of the inventories. However, there is not much systematic research about what comes after that: the use of the data and results, and what can be learned about the specific requirements and interests of the actual and potential users. In preparation for BWI 2002, BMEL (the responsible Federal Ministry of Food and Agriculture) consulted with all Federal States about the usage of the NFI results. The relevance of statistically sound forest data had been confirmed then, in particular for the monitoring of forest development and forest productivity, for the adaptation of yield tables, and for the planning of capacities of the wood processing industries.

While recent internet searches reveal that the wealth of NFI data is both taken up in an increasing number of research studies and also taken up by the general public and journalists, a systematic follow-up on the use of the NFI results has not been done for the German NFI so far. A first users' conference on NFI data is therefore planned for the near future.

As in many other countries, the German NFI has developed towards a dynamic system and a permanent program for the provision of information on forests considering both the resource and the ecosystem forest. The federal system in Germany poses particular challenges to the implementation of a national-level program such as this. After intensive discussions about the establishment of such a comprehensive national-level monitoring system in the 1970 and 1980s, the NFI has also become a well-established, valuable, and frequently referenced source of quality-approved forest data and information in Germany.

8. ABSTRACT

German forestry is known for its long history of sustainable forest management. However, a country-level forest inventory (national forest inventory, NFI) with a statistical basis, has only been implemented since the 1960s in the German Democratic Republic (GDR, Eastern Germany), and the 1980s in the Federal Republic of Germany (FRG, Western Germany). This is relatively late when compared to other countries. In this paper, an overview is given of the history of large-area forest assessments in Germany, and the developments towards a national forest inventory. In addition, an elaboration, as well as a brief outlook, are given on the adaptations of this monitoring system over time to the changing needs of a broadening group of stakeholders and interested parties.

9. ZUSAMMENFASSUNG

Titel des Beitrages: *Die Geschichte der Bundeswaldinventur: Eine umfassende Datenquelle zum Wald in Deutschland.*

Die Waldbewirtschaftung in Deutschland ist für ihre lange Tradition der Nachhaltigkeit bekannt. Eine nationale Waldinventur auf statistischer Basis fand jedoch erst in den 1960er-Jahren in der DDR und Ende der 1980er-Jahre in der BRD statt; dies ist vergleichsweise spät im Vergleich zu anderen Ländern. In diesem Aufsatz geben wir einen Überblick über die Geschichte großräumiger Walderfassungen in Deutschland und erläutern die Entwicklung hin zur ersten Bundeswaldinventur in 1987. Wir dokumentieren die Änderungen über die Zeit, die die Bundeswaldinventur erfahren hat in Reaktion auf sich ändernde Anforderungen, und geben einen kurzen Ausblick.

10. RÉSUMÉ

Titre de l'article: *L'Inventaire Forestier national en Allemagne: répondre aux besoins d'information liés aux forêts.*

La gestion des forêts en Allemagne est connue pour sa longue tradition de pérennité. Toutefois, un inventaire forestier national sur une base statistique n'a été réalisé que dans les années 1960 en RDA et à la fin des années 1980 en RFA, ce qui est relativement tardif par rapport à d'autres pays. Dans cet article, nous donnons un aperçu de l'histoire des inventaires forestiers à grande échelle en Allemagne et nous expliquons l'évolution vers le premier inventaire forestier fédéral en 1987. Nous documentons les changements au fil du temps que l'inventaire forestier fédéral a subis en réponse à l'évolution des besoins et nous donnons une brève perspective.

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