Stubborn and adaptive – five decades of monitoring and research of self-regulated tree demography in Lower Saxony, Germany[1)]

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PETER MEYER[*)]

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*) Korrespondierender Autor: DR. PETER MEYER. Nordwestdeutsche Forstliche Versuchsanstalt, Sachgebiet Waldnaturschutz/Naturwaldforschung, Grätzelstraße 2, D-37079 Göttingen. E-Mail: Peter.Meyer@nw-fva.de

1) Dedicated to Hermann SPELLMANN with deep gratitude and great admiration for his commitment to and support of long-term investigations in forests.

1. INTRODUCTION

Against the backdrop of accelerating human induced environmental change, long-term ecological monitoring and research continues to gain significance (PARR et al., 2002; SPELLERBERG, 2005; PEREIRA et al., 2006). However, long-term monitoring is liable to failure and often falls short of realizing its potential (LINDENMAYER and LIKENS, 2010a). Learning from the experiences made with long-standing monitoring schemes may help to improve existing designs and to plan successful new programs.

There is a wide consensus among ecologists that long-term research is necessary, in order to gain understanding of several key features of ecosystems, notably slow processes, rare events or processes with high variability and complex interactions (FRANKLIN, 1989; PICKETT, 1989; TILMAN, 1989; FISCHER, 1997; LINDENMAYER and LIKENS, 2010a; MÜLLER, 2010; HAASE et al., 2018; PRETZSCH et al., 2019).

Long-term research in set aside strict forest reserves (SFR) reveals the transition from a managed to a mainly self-regulated forest ecosystem. In view of the eradication of primeval forests in western central Europe (SABATINI et al., 2018), the initial idea behind SFR programs was to better understand the natural state and dynamics of forests on different sites and in different regions (LAMPRECHT et al., 1974). In particular, understanding of natural forest development is of fundamental importance for close-to-nature forestry and nature protection (SPELLMANN, 1997; SCHÜTZ, 2002), to evaluate the impacts of forest management (FRELICH et al., 2005) and to ensure ecosystem function, which in turn is the basis for the provision of ecosystem services (MORI et al., 2018). The extent to which natural forest ecosystems can cope with accelerating human induced environmental change is, however, uncertain. In this context, set-aside forests can help to understand the intrinsic resilience of forest ecosystems, even under global change (MEYER et al., 2017) and, consequently, are an important component of adaptive management systems (WALTERS, 1986; HOLLING and MEFFE, 1996). From a conservation point of view, natural ecosystems constitute the heritage to be preserved for future generations (WATSON et al., 2018), making the degree of naturalness one of the most relevant criteria in decisions on conservation priorities (ANGERMEIER, 2000). Consequently, it appears that the long-term research of self-regulated forest development has high potential to contribute significantly to key questions of forestry, conservation biology and ecology in general.

The observation of tree demography and forest structure in SFR – and partly also in naturally developing forests in other protected areas – is among the longest standing ecological monitoring schemes in central Europe (BÜCKING, 2013). In the majority of German states, SFR programs commenced in the 1960's – 1970's and have been running since then (MEYER et al., 2007). Meanwhile, a network of 743 SFR, covering an area of more than 35,000 hectares, has been left to natural development in order to investigate self-regulated dynamics of formerly managed forests. The unique features of SFR monitoring are, first, the observation of self-regulated forest dynamics and second, to monitor a system of several SFR representing the natural variability of site conditions and forest communities (PROJEKTGRUPPE NATURWALDRESERVATE, 1993; MEYER et al., 2007).

A balance of what has so far been achieved, on the basis of SFR research reveals a differentiated picture. While there are few examples where long-term research in SFR has contributed to silviculture (BRANG, 2005), substantial results on vegetation dynamics (BRUNET et al., 1996, 2010; SCHMIDT, 1999; SCHMIDT and SCHMIDT, 2007; KOMPA and SCHMIDT, 2010; HEINRICHS et al., 2011; PLUE et al., 2013) have been acquired. Also, long-term studies on the development of forest structure in SFR (HEIRI et al., 2009, 2011; MEYER et al., 2016) are emerging. Time series data from SFR have moreover been employed to study the as yet poorly understood process of tree mortality (HÜLSMANN et al., 2016, 2017, 2018; MEYER and MÖLDER, 2017), the shift of tree species composition (MEYER, 1997; ROHNER et al., 2012) and the self-regulated dynamics of old growth attributes (VANDEKERKHOVE et al., 2009, 2018; MEYER and SCHMIDT, 2011; PAILLET et al., 2015). This balance shows that long-term investigations in SFR are beginning to play a significant role in forest ecology.

Since the 1990's the main question expected to be answered by SFR research was whether discontinuing or ongoing forest management show contrasting effects on biodiversity (ALBRECHT, 1990; AMMER, 1992; MEYER, 2018). The dominance of this topic resulted from an ongoing controversy over protection issues in Germany's forests (AMMER et al., 1989; OTTO, 1991; HOFMANN et al., 2000; MEYER, 2013; BÄSSLER and MÜLLER, 2015; SCHULZE and AMMER, 2015; SCHULZE, 2018; SCHULZE et al., 2018), which has further been inflamed by the target to leave 5% of the forest area of Germany to natural development (BMU, 2007; ENGEL et al., 2019). In Germany, a large number of one-off comparative studies along gradients of management intensity or naturalness have been conducted to address this issue (DETSCH, 1999; AMMER and UTSCHICK, 2004; AMMER and SCHUBERT, 1999; HÄRDTLE et al., 2001; WESTPHAL, 2001; Müller, 2005; VON OHEIMB, 2003; VON OHEIMB et al., 2005; WINTER, 2005; Winter et al., 2005; MÜLLER et al., 2007; AMMER et al., 2017). In the majority of these studies SFR represent maximum naturalness or minimum management intensity, respectively. Yet, time-series studies on biodiversity issues in SFR, except for vascular plants, are scarce. To date, the results of one-off comparative studies have been heterogeneous and partly contradictory (cf. PAILLET et al., 2010; DIELER et al., 2017). Besides the overall variability of forests with respect to disturbances, management history and site conditions (SCHALL et al., 2018; PENONE et al., 2019) this can be attributed to problems of comparability, an all too simple classification of forest management, hidden assumptions on naturalness and a too short duration of non-management (MEYER, 2018). A slowdown of the controversy over the effects of forest management on biodiversity and whether it is reasonable to set aside a certain forest area from management is not observable (SOTIROV et al., 2017).

After five decades of continued monitoring of tree demography and forest structure in SFR of Lower Saxony, Germany, we concerned ourselves with the evolution of the program over time, in order to point out strengths and weaknesses and to further develop the conceptual foundation. As a template we employed the concept of adaptive monitoring, proposed by LINDENMAYER and LIKENS (2009) to achieve target-orientation and thus secure success of long-term ecological monitoring and research.

In our study we focused on western central Europe because the SFR of Lower Saxony, Germany, are considered to be representative for this region. We intended to, 1) point out general epistemological problems of long-term SFR research, 2) give an account of the development and state of the art of the SFR program in Lower Saxony and review its strengths and weaknesses, 3) refine the conceptual model underlying the investigation of tree demography and structural dynamics, and, 4) point out key lessons for long-term research in SFR.

1.1 General epistemological problems of long-term monitoring

Two epistemological problems accompanied the SFR-program in Lower Saxony, which we regard to be typical for almost all cross-generational monitoring schemes collecting a large amount of diverse data. The first problem was to guarantee that monitoring is properly orientated to the research goal (target-orientation), and the second was to prevent subjectively biased analysis of the growing pool of data.

Guaranteeing target-orientation is regarded to be an intrinsic problem that long-term ecological research has to cope with (MEYER, 1997). As future ecological questions are not precisely foreseeable decades ahead, the already established time-series are not always suitable to address current matters. Formulating precise hypothesis at the start entails a high risk of ending up with irrelevance decades later when testing the hypothesis is due. Also, simply adding further assessments to address fashionable questions has to be discarded, because the concurrent requirement to ensure the integrity of time-series would inevitably lead to ever growing expenses which in turn may eventually exceed an accepted limit.

This problem area becomes apparent when evaluating the first conceptual publications which paved the way for the establishment of the research program (HESMER, 1934; HUECK, 1937; SCAMONI, 1953; TRAUTMANN, 1969; LAMPRECHT, 1969). In these publications, only general issues had been proposed for studying SFR. Several of them are still relevant to date, e. g. site-specific natural tree species composition. Others had not been anticipated, e. g. dead wood dynamics or carbon storage and release, but appear to be currently relevant. The protocol for data collection was more or less transferred from classical approaches (LEIBUNDGUT, 1959) already applied in primeval forest research in Europe.

The following generations of researchers in charge of the program had to decide how to deal with the given plot design, protocol and collected dataset. Thus, a procedural problem ("how to") and not a precise question ("why") was of primary importance. This situation is fundamentally different from the approach of confirmatory research (CDA; s. WAGENMAKERS et al., 2012), in that the dataset and not a hypothesis becomes the starting point. This, however, gives rise to the second characteristic problem of long-term monitoring and research. Subjectively biased data analysis can become a serious epistemological problem when exploring datasets (STERLING et al., 1995). With increasing size and complexity of a given dataset, the number of possible research questions and, different subsets and methods for statistical analysis increases exponentially. More possibilities create more leeway for subjectivity. Usually in long-term monitoring and research, precise and operational research questions are framed ex post in view of the possibilities the database offers. This practice is susceptible to adapting questions to results (LINDENMAYER and LIKENS, 2010b) and thus fall victim to subjectivity.

A widely accepted method for avoiding subjectivity is to strictly follow the hypothetical-deductive or falsification approach (FREY, 1970; POPPER, 1979), underlying CDA. The central idea is that one hypothesis or model is examined within one crucial experiment. As long as the hypothesis cannot be falsified it stays in place and new sub-hypothesis are generated and scrutinized experimentally. It is critical that hypothesis building precedes the data analysis (ARMSTRONG, 1970). In scientific practice, however, the independence of hypothesis building and testing is often violated, as many studies declared confirmatory are in fact exploratory (STERLING et al., 1995; GAUSS et al., 2015). This practice triggered a serious reproducibility crisis in science (IOANNIDIS, 2005; BAKER, 2016; GELMAN and GEURTZ, 2017) and raised concerns about cognitive fallacies and self-deception (NUZZO, 2015).

Preventing subjectively biased data analysis requires finding solutions to the problem of exploring an already existing data pool in an objective way. Explorative data analysis is intended to reveal patterns and inferences within a complex dataset (HEILER and MICHELS, 1994). The majority of our ecological knowledge has been gathered by explorative and observational studies, simply because the complexity of both natural and man-made ecological systems makes it impossible to comprehensively capture their real world behavior with classical experiments (FAGERSTRÖM, 1987). As a consequence, ecology resembles the work of a detective (HILBORN and MANGEL, 1997) putting together single findings to create a valid, though incomplete, picture of causes and effects within complex ecological systems. In that light, observational and explorative studies are essential to improve our understanding of complex systems, such as forests.

In view of the financial input into monitoring programs and the rapidly increasing amount of environmental data, it is of great interest to make use of this information without subjective bias. This requires considering exploratory approaches to be complementary to, rather than competing with CDA (TUKEY, 1980) and finding a formalized way of defining tractable hypothesis.

Long-term SFR research follows an observational and explorative approach with the intention to capture the real world complexity of naturally developing forests, which is, however, confronted with the epistemological problems of how to secure target-orientation, and how to prevent subjectively biased data analysis.

1.2 History and current state of the SFR program

To date the basic idea of monitoring SFR in Lower Saxony was to observe the main processes of tree demography and the structural dynamics within the observed tree stands (MEYER, 1996). Staff levels and financial resources did not allow for additional systematic assessments in other fields. However, a long standing cooperation with the Institute of Silviculture, Göttingen, led to the development and application of a standard methodology for monitoring vegetation in several SFR (SCHMIDT and SCHMIDT, 2007).

In Lower Saxony 63 SFR were designated in the 1970's, comprising an area of 1,000 ha. Since then the SFR network has increased to 107 SFR with an area of 4,576 ha (*Fig. 1*). However, several initial SFR have also been given up in the meantime, mainly because it was feared that endangered species would be threatened by natural forest development (MEYER, 1995). It is intended that the network will increase in future by incorporating many of the newly designated naturally developing forests in Lower Saxony.

The core areas (CA) were the first plots established in the 1970's to monitor forest structure. They comprise a rectangular area of ca. 1 hectare and were established to represent a typical section of the forest community. The CA network covers a wide range of different forest types on a variety of sites (*Tab. 1*).

The protocol for CA monitoring mainly focused on diameter and height of the living tree stand ≥ 4 cm diameter at breast height (dbh). In the 1980's, emerging topics like dead wood, the interest in a better spatial representation of forest structure and the relevance of tree regeneration meant that the protocol for CA-monitoring was modified (NORDWESTDEUTSCHE FORSTLICHE VERSUCHSANSTALT, 2017) and, in addition, sampling on circular plots (CP) was implemented (MEYER and FRICKE, 2018).

It became apparent that monitoring of CA and CP needed a conceptual foundation, in order to generate a data pool for multiple use, while ensuring the integrity of measurements. The developed model was based on the fundamental demographic processes of the tree population (MEYER, 1997). The implementation of dead wood and tree regeneration resulted in three monitoring compartments:

1) standing live and dead trees and shrubs ≥ 7 cm dbh,

2) lying living trees and dead wood ≥ 7 cm diameter,

3) living trees and shrubs < 7 cm dbh and more than one year old.

An important innovation was the assessment of the positions of all standing trees and shrubs ≥ 7 cm dbh and all lying objects ≥ 20 cm diameter at the butt end. To generate time series of the spatial distribution of stand-

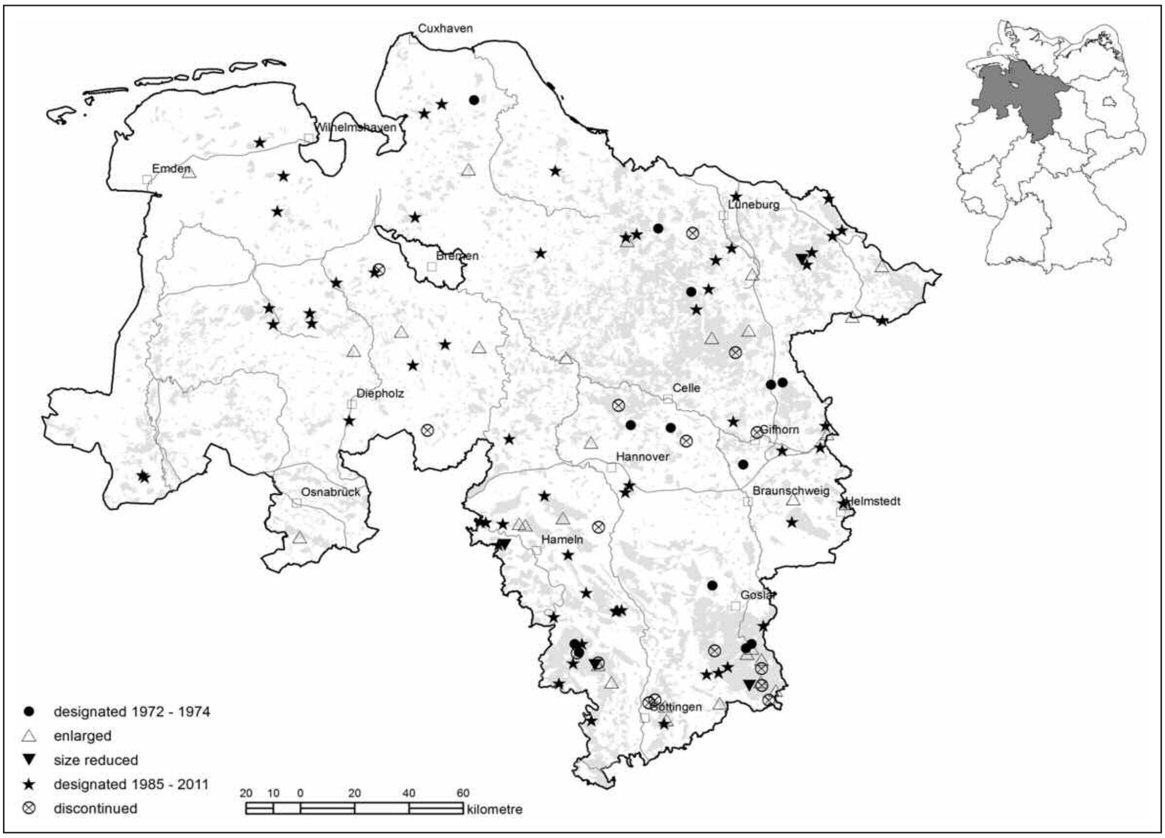

Fig. 1

The network of strict forest reserves in Lower Saxony, Germany in the year 2019 and its development since 1972.

Naturwälder in Niedersachsen im Jahr 2019 und die Entwicklung des Flächensystems seit 1972.

Tab. 1

Number of core areas (left number) and SFR with core areas (right number) per forest type, site conditions and study duration (cut-off year 2019). The maximum study duration amounts to 49 years. – = site conditions not typical for the respective forest type, 0 = no core area designated. *1 left side: number of CA, right side: number of SFR.

Anzahl an Kernflächen je Bestockungstyp, Standortbedingungen und Beobachtungsdauer (Stichjahr 2019). Die maximale Beobachtungsdauer beträgt 49 Jahre. – = Standortbedingungen untypisch, 0 = keine Kernfläche vorhanden. *1 linke Seite: Anzahl Kernflächen, rechte Seite: Anzahl Naturwälder.

forest type	study duration [years]	oligotrophic			mesotrophic			eutrophic			sum[*1]
		water excess	regular	water shortage	water excess	regular	water shortage	water excess	regular	water shortage	
pure and mixed beech	one obs.	-	4/2	0	-	1/1	0	-	1/1	0	6/4
	< 25	-	8/5	0	-	4/3	0	-	8/6	1/1	21/15
	≥ 25	-	6/4	1/1	-	2/2	0	-	11/8	3/3	23/16
mixed oak	one obs.	0	0	0	1/1	0	0	0	1/1	0	2/2
	< 25	0	0	0	1/1	1/1	0	2/2	1/1	0	5/4
	≥ 25	0	6/4	0	0	3/3	0	1/1	1/1	0	11/9
mixed ash/elm	one obs.	-	-	-	-	-	-	0	0	0	0
	< 25	-	-	-	-	-	-	0	2/2	0	2/2
	≥ 25	-	-	-	-	-	-	0	1/1	0	1/1
mixed birch	one obs.	0	0	0	-	-	-	-	-	-	0
	< 25	2/2	0	0	-	-	-	-	-	-	2/2
	≥ 25	2/2	0	1/1	-	-	-	-	-	-	3/3
pure and mixed alder	one obs.	-	-	-	1/1	-	-	0	-	-	1/1
	< 25	-	-	-	0	-	-	0	-	-	0
	≥ 25	-	-	-	1/1	-	-	2/1	-	-	3/2
pure and mixed spruce	one obs.	0	0	-	-	-	-	-	-	-	0
	< 25 y.	0	2/2	-	-	-	-	-	-	-	2/2
	≥ 25	0	4/3	-	-	-	-	-	-	-	4/3
pure and mixed pine	one obs.	0	0	1/1	-	-	-	-	-	-	1/1
	< 25 y.	0	2/2	4/3	-	-	-	-	-	-	6/5
	≥ 25	0	0	3/1	-	-	-	-	-	-	3/1
sum[*1]		4/3	32/20	10/7	4/4	11/9	0	5/3	26/16	4/3	96/55

ing trees from the onset of measurement, the positions of all trees of the first and second inventory ≥ 7 cm dbh were reconstructed. This proved to be very time-consuming, yet it offers the opportunity for the spatially explicit analysis of structural dynamics (PRETZSCH et al., 2010) and demographic process like tree mortality (MEYER and MÖLDER, 2017). Tree and shrub regeneration was assessed on subplots of 50 m^2 centered at the crossing points of a 20 x 20 m grid network.

In the 1990's the extended protocol, additional SFR and inventories on CP made the assessments significantly more laborious. Also, more time was needed for data management and analysis. Four measures were taken to overcome the resulting temporal and staffing bottlenecks. First, to restrict CP inventories to a subset of 34 representative SFR (MEYER et al., 2006). Second, to reduce the number of CA from 137 to 96. Third, to extend the turnover time of inventories. The resulting longer observation periods and asynchronous record dates were regarded as a minor disadvantage compared to the priorities of data management and increasing scientific output. Fourth, to implement a digital data collection system with a specialized software for forest inventories (IFER, 2019; FieldMap) which has increased the efficiency of assessments and subsequent data processing significantly since 2004.

As a result a complete work-flow for monitoring tree populations was established consisting of 8 work packages: field assessments – quality control of field data – data processing and storage – standardized data exploration – derivation of admissible and relevant hypothesis – if appropriate: compilation of additional data – data analysis – publication of results. A maximum overlap between the working areas of field workers and scientists proved to be a pre-requisite to ensure high data quality and fast data processing. Meanwhile, the third assessment was completed in most of the initial CA and tree positions were reconstructed. Several national parks and biosphere reserves in Germany have adopted the protocol for CP inventories as well as the linked work packages, including standardized data analysis (s. SPORS et al., 2018).

1.3 Strength and weaknesses of the monitoring program

According to LINDENMAYER and LIKENS (2010b) tractable guiding questions, a conceptual model of how the monitored ecosystem works, an experimental approach, effective data management, dedicated leadership, skilled and motivated field staff, scientific output and continuity of the necessary resources are of central importance for successful long-term monitoring.

Tractable research questions did not guide the design of the monitoring scheme from the beginning on. To solve the problem of target orientation in the 1990's a conceptual model was developed and the protocol was adapted to this model. The SFR program in Lower Saxony was since then consciously designed to do "science backwards" in an as objective as possible manner. Corresponding to adaptive monitoring the conceptual model served as crux of the matter.

An experimental approach was missing in SFR research in Lower Saxony. Looking back, it would have been advantageous to conceptualize SFR as a control against which to measure the effects of forest management. Several German states have realized this long-term comparative approach in assessing both SFR and regularly managed forests (ALTHOFF et al., 1993; MEYER et al., 2004).

It is a common experience in long-term studies that the efforts necessary for data management and analysis are underestimated (LINDENMAYER and LIKENS, 2010b). Also, in the SFR program in the 1990's the increasing amount of inventory data made an even stronger focus on data management necessary. It was not before the 2000's that a database containing the data of CA, CP as well as diverse environmental data was built up. We simultaneously attempted to strengthen data analysis and output by working on a compilation of the main results of research for all SFR. This project resulted in two books (MEYER et al., 2006, 2015), fostered investments into data management and gave orientation as to

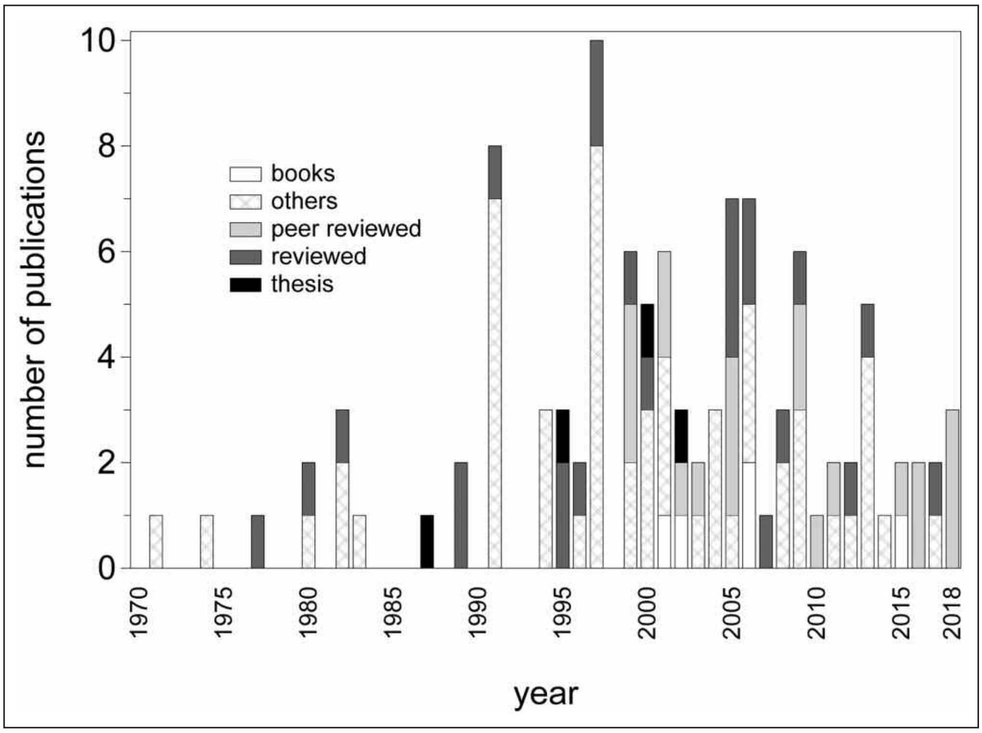

Fig. 2

Publications on SFR in Lower Saxony authored and/or initiated by the persons responsible for monitoring and research in SFR in Lower Saxony, Germany from 1970 – 2018 (thesis = ph. d. thesis, reviewed = reviewed by the editors).

Publikationen über Naturwälder in Niedersachsen von 1970 bis 2018, in denen die Verantwortlichen für die Naturwaldforschung Haupt- oder Ko-Autoren sind oder die durch sie wesentlich unterstützt wurden.

the degree of data quality and which type of data should be stored. It was advantageous that since 1991 the SAS™ System continued to be available for data analysis. This continuity made it possible to develop and sustain a comprehensive library of source codes.

After an initial phase at the Institute of Silviculture, Göttingen, monitoring and research in SFR has been conducted since 1986 at the Northwestern Forest Research Institute (NW-FVA, formerly: Lower Saxony Forest Research Institute). The shift of responsibility to an institution with a long tradition and high appreciation of long-term research in several fields (SPELLMANN, 1997, 2006; SPELLMANN et al., 1997) is regarded to be crucial for the survival of the SFR program. Permanently employed skilled and dedicated field staff as well as scientists with a passion for long-term research had the opportunity to conduct the program.

Focusing on long-term assessments and data gathering entails the risk that making scientific use of the data comes off badly. Although in SFR in Lower Saxony numerous studies have been conducted (MEYER et al., 2006, 2015), peer reviewed publications first began to play a role at the end of the 1990's and still do not build the majority (*Fig. 2*). In view of the high potential of the existing data pool it seems that more effort needs to be invested in this. An already successful strategy was to contribute monitoring data to coordinated publication projects with universities and other research institutes (HÜLSMANN et al., 2016, 2017, 2018).

Parallel to the ongoing controversy over protection issues in Germany's forests (MEYER et al., 2019), financial and staff resources have been supplied at an increasing rate. Under these circumstances, the SFR scheme in Lower Saxony has developed into a functioning long-term monitoring program, albeit with shortcomings in scientific impact.

1.4 The conceptual model of long-term research of tree demography in SFR

Adaptive monitoring (LINDENMAYER and LIKENS, 2009) comes from the central idea that long-term studies need a conceptual model of the objects and processes under investigation, which serves as a basis for designing and adapting the methodology to relevant questions. Although not under this name, the SFR program has followed the approach of adaptive monitoring for more than two decades.

The initiative to develop a conceptual model for monitoring tree populations in SFR was driven by an analysis of the monitoring data on the tree populations in CA (MEYER, 1995). The model depicted growth, mortality, ingrowth and decay as central processes and assigned these and structure attributes to the assessed compartments of the tree population (MEYER, 1997). This conceptual model has been refined (*Fig. 3*, *Tab. 2–4*). Designed in the style of a game board it offers a formalized description of the compartments, processes, structures, driving factors and relationships which can be taken

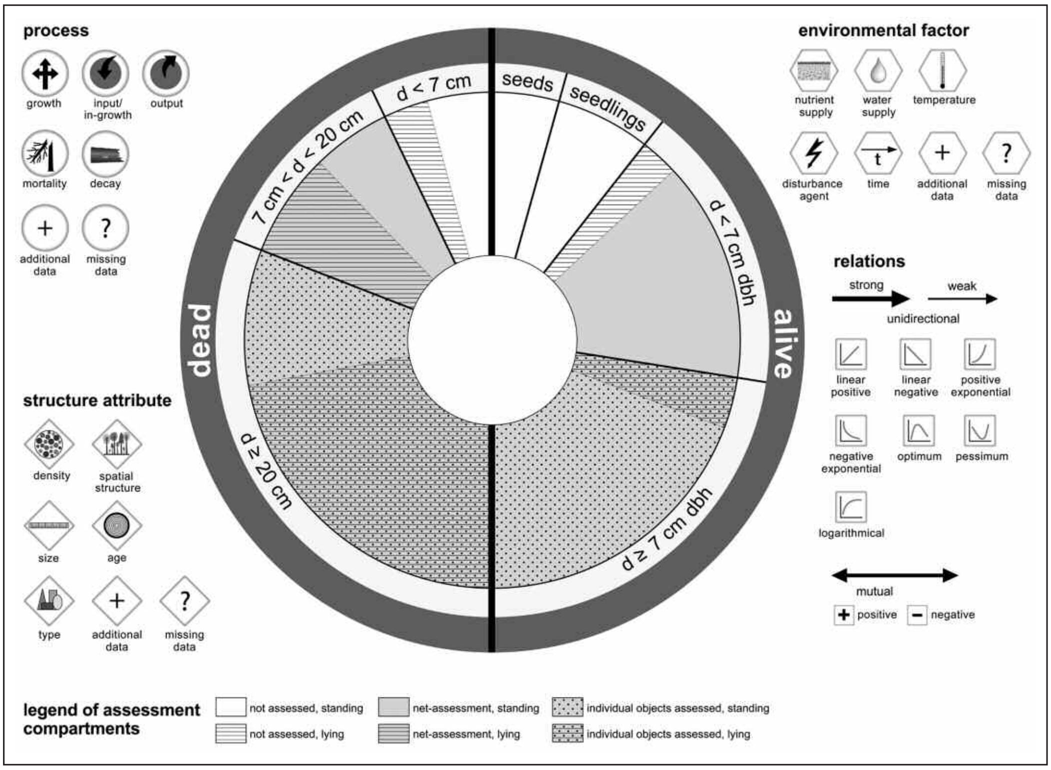

Fig. 3

Conceptual model of processes, structures, environmental factors, relations and assessed compartments underlying monitoring and hypothesis building of SFR in Lower Saxony, Germany.

Das konzeptionelle Modell der Prozesse, Strukturen, Einflussfaktoren, Beziehungen und Erfassungskompartimente, das dem Monitoring und der Hypothesenbildung in der niedersächsischen Naturwaldforschung zugrunde liegt.

Tab. 2

Basic processes monitored in CA, their operationalization, the reference object the process is attributed to and the degree to which monitoring is conducted per compartment (● = complete, **O = in part, ○ = missing or irrelevant). Monitoring compartments are: SL7 = standing alive trees and shrubs with dbh ≥ 7 cm, SD7 = standing dead trees and shrubs with dbh ≥ 7 cm, LD20 = lying alive and dead trees, shrubs and dead wood pieces with d ≥ 20 cm, LD7_20 = lying alive and dead trees, shrubs and dead wood pieces with 7 ≤ d < 20 cm, SLR = standing alive trees and shrubs < 7 cm dbh = regeneration (seedlings are excluded, i. e. only plants are counted which are older than one growing season).**

Wichtigste Prozesse, die in Kernflächen erfasst werden, deren Operationalisierung und Bezugsobjekt sowie die Erfassungstiefe je Aufnahmekompartiment (● = vollständig, **O = teilweiset, ○ = nicht erfasst oder irrelevant). Aufnahmekompartimente sind: SL7 = stehende lebende Bäume und Sträucher mit BHD ≥ 7 cm, SD7 = stehende tote Bäume und Sträucher mit BHD ≥ 7 cm, LD20 = liegende lebende und tote Bäume, Sträucher und Totholzstücke mit einem Durchmesser ≥ 20 cm, LD7_20 = liegende lebende und tote Bäume, Sträucher und Totholzstücke mit einem Durchmesser > = 7 und < 20 cm, SLR = stehende lebende Bäume und Sträucher mit BHD < 7 cm = Verjüngung (Keimlinge ausgeschlossen, d. h. nur Pflanzen zu zählen, die älter als eine Vegetationsperiode sind).**

process	operationalisation	primary reference object	monitoring compartment				
			SL7	SD7	LD20	LD7_20	SLR
growth	growth of diameter, basal area, height, volume or biomass a^{-1}	individual	●	○	**O**	**O**	**O**
	growth of basal area, volume or biomass a^{-1} ha^{-1}	stand	●	○	**O**	**O**	**O**
mortality	number, basal area, volume or biomass of additional dead trees/shrubs a^{-1} ha^{-1}	stand	●	○	**O**	**O**	○
input/ ingrowth	number, basal area, volume or biomass of additional living trees/shrubs a^{-1} ha^{-1}	stand	●	○	**O**	**O**	○
	number or volume of additional dead trees/shrubs or dead wood pieces a^{-1} ha^{-1}	stand	○	●	●	○	○
output	number or volume of missing dead trees/shrubs or dead wood pieces a^{-1} ha^{-1}	stand	○	●	●	○	○
decay	volume decrease of remaining dead trees/shrubs and dead wood pieces a^{-1}	individual/ piece	○	●	●	○	○

into consideration to study self-regulated tree population dynamics in SFR.

Compromises had to be made with regard to monitoring intensity per compartment, in order to ensure feasibility. Thus, monitoring of individual re-identified trees and snags starts from a threshold of 7 cm dbh. The assessment of seed distribution was excluded because maintaining seed traps on all plots would have exceeded the available capacities. The same holds true for the monitoring of recruitment, growth and mortality of individuals < 7 cm dbh. Thus, monitoring in the living stand is restricted to in-growth, growth and mortality of trees ≥ 7 cm dbh, and net changes are monitored for saplings and small trees < 7 cm dbh.

In respect of dead wood, input and decay of individual objects ≥ 20 cm diameter at the butt end (dbe) are monitored on the basis of coordinates. Dead wood objects ≥ 7 cm and < 20 cm dbe are assessed in summary on CA and excluded from CP-monitoring. Dead wood < 7 cm dbe is not considered at all.

Besides individual based and net-processes, five broad categories of structures were defined (*Fig. 3*, *Tab. 3*) which are either associated with single trees (type, size, age), or with groups or stands of trees (density, spatial structure). Because there are multiple ways to quantify and analyze stand density and structure (PRETZSCH, 1993, 2010; POMMERNING, 2002; ZEIDE, 2005) further operationalization was not regarded as practical, in order to avoid narrowing the scope unnecessarily.

Disturbance agents, nutrient and water supply as well as temperature regime are regarded to be of principal importance for constructing hypothesis on causes and effects (*Tab. 4*). Time itself is seen as an additional factor. Here, we assumed that SFR are subject to a transformation process, where the imprints of former management are gradually fading out, thus making time since abandonment an important predictor. Time also represents the intrinsic development of the tree populations.

1.5 Example of hypothesis building

The conceptual model serves to guarantee that hypothesis are framed in a transparent and formalized way before the data analysis is started. Hypothesis are constructed by connecting processes, structures and factors with relationships. As an example, a hypothesis is constructed, visualized with the conceptual model, commented and further developed:

H1: With time since abandonment from management the diversity of the vertical structure in beech SFR is decreasing (*Fig. 4*, left).

The background for this hypothesis is the widely held view that setting aside beech forests results in homogenously structured stands (e. g. HOFMANN and JENSEN, 1996). This hypothesis, however, blanks out the possibly diversifying effect of senescence and disturbances on structural development. With increasing age, the disturbance rate might also increase. Thus, it is necessary to define the age- and time-scale for which this hypothesis is regarded to be valid. Most of the beech SFR in Lower Saxony comprise stands aged 100–160 years at the time of designation. The maximum period of time observed spans 30–50 years. Furthermore, the modifying effect of site conditions deserves closer attention, as there are indications that with better nutrient supply shade tolerance increases (KOBE et al., 1995; WALTERS and REICH, 2000). Additionally, species of the genera *Acer*, *Fraxinus* and *Ulmus*, which are characterized by abundant seeding, come into play on nutrient rich soils, favouring the formation of a regeneration and shrub layer. Taking these considerations into account, an improved sequence of hypothesis is developed (*Fig. 4*, right):

Tab. 3

Basic structure attributes of CA monitoring, their operationalization, the reference object the attribute is associated with and the compartment for which data are acquired (● = complete, **o = in part, ○ = missing or irrelevant). Monitoring compartments are: SL7 = standing alive trees and shrubs with dbh ≥ 7 cm, SD7 = standing dead trees and shrubs with dbh ≥ 7 cm, LD20 = lying alive and dead trees, shrubs and dead wood pieces with dbe ≥ 20 cm, LD7_20 = lying alive and dead trees, shrubs and dead wood pieces with 7 ≥ dbe < 20 cm, SLR = standing alive trees and shrubs < 7 cm dbh = regeneration (seedlings are excluded, i. e. only plants are counted which are older than one growing season).**

Wichtigste Strukturen, die in Kernflächen erfasst werden, deren Operationalisierung und Bezugsobjekt sowie die Erfassungstiefe je Aufnahmekompartiment (● = vollständig, **o = teilweiset, ○ = nicht erfasst oder irrelevant). Aufnahmekompartimente sind: SL7 = stehende lebende Bäume und Sträucher mit BHD ≥ 7 cm, SD7 = stehende tote Bäume und Sträucher mit BHD ≥ 7 cm, LD20 = liegende lebende und tote Bäume, Sträucher und Totholzstücke mit einem Durchmesser ≥ 20 cm, LD7_20 = liegende lebende und tote Bäume, Sträucher und Totholzstücke mit einem Durchmesser > = 7 cm und < 20 cm, SLR = stehende lebende Bäume und Sträucher mit BHD < 7 cm = Verjüngung (Keimlinge ausgeschlossen, d. h. nur Pflanzen zu zählen, die älter als eine Vegetationsperiode sind).**

structure attribute	operationalisation	primary reference object	monitoring compartment SA7	SD7	LD20	LD7_20	SLR
density	number, basal area, volume or biomass of living trees/shrubs ha^{-1}	stand	●	●	●	●	●
spatial structure	vertical distribution of individuals (layering) *1	stand	●	○	○	○	●
	horizontal distribution of individuals (pattern): many parameters available*1	stand	●	●	●	●	**o**
	three dimensional distribution of biomass: several possibilities*1	stand	●	●	●	●	●
size/dimension	distributions and their statistical parameters in respect of diameter, basal area or height/length	individual	●	●	●	●	●
type	frequency distributions and diversity measures of species, object types (cavity tree, snag, …), or other	individual	●	●	●	●	●
age	recorded or estimated age in years	individual	●	**o**	**o**	○	○

*1 for detailed operationalization s. e. g. PRETZSCH 2010 or POMMERENING 2002.

Tab. 4

Basic environmental factors applied in hypothesis building in CA monitoring, their operationalization and the data origin.

Grundlegende Einflussfaktoren für die Hypothesenbildung beim Kernflächenmonitoring, deren Operationalisierung und die Datenquelle.

environmental factor	operationalisation	data origin
nutrient supply	18 ranks	forest site mapping Lower Saxony*1
water supply	8 categories without water surplus, 4 with water surplus, mires	forest site mapping Lower Saxony*1
	height a. s. l., slope and exposition	topographic map, digital terrain model
	precipitation a^{-1} or season	meteorological data
temperature	length of growing season	meteorological data
	extreme events (drought, frost)	meteorological data
disturbance agents	herbivores, pests, pathogens	reports; CA monitoring
	storms, hurricanes	reports; meteorological data; CA monitoring
	extreme meteorological events (drought, frost, excessive rainfall)	reports; CA monitoring
	fire	reports; CA monitoring
	snow and geological events (avalanche, landslide, …)	reports; meteorological data; CA monitoring

*1 s. SCHMIDT et al. (2015).

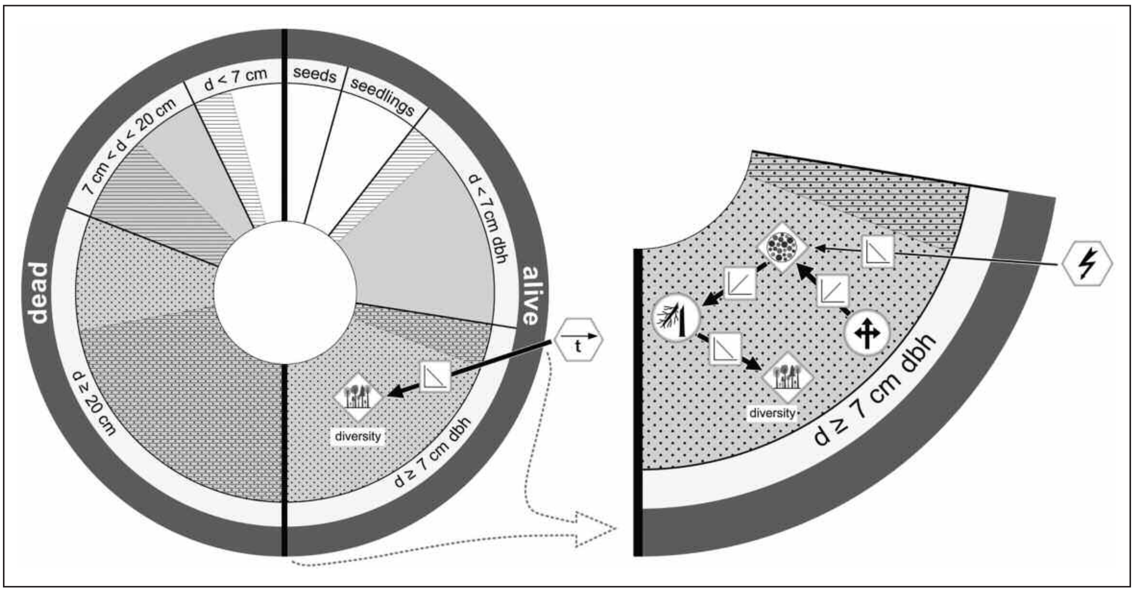

Fig. 4

Example of hypothesis building on basis of the conceptual model (s. *Fig. 3*).
Left: initial simple hypothesis, right: further developed hypothesis; for details s. text.

Beispiel für die schrittweise Hypothesenbildung auf Grundlage des konzeptionellen Modells (*Fig. 3*).
Links: einfache Hypothese, rechts: weiter entwickelte Hypothese; Erläuterungen s. Text.

In the first decades after abandonment from management …

H1a … disturbances do not reverse the intrinsic trend of increasing stand density in older beech (100 – 160 years) stands,

H1b … increasing stand density leads to increasing density dependent mortality of beech trees,

H1c this relationship is mitigated with increasing nutrient supply.

We feel that, for the time being, it is advisable to end with H1c and not to address the issue of admixed species and regeneration processes, in order to keep the investigation manageable. The next step would be to decide which sub-set of data is suitable to test the hypothesis. As CA data cover the longest period of time and are large enough to allow for spatially explicit analysis it is reasonable to select all 23 pure and mixed beech CA in 16 SFR for data analysis (*Tab. 1*).

2. CONCLUSIONS

The evaluation of long-term SFR research in Lower Saxony showed that designing and further developing a long-term program as an adaptive question-driven monitoring (LINDENMAYER and LIKENS, 2010) is a promising way to secure the continuity and, above all, the relevance of the program. Our experience is that a conceptual model of the ecosystem to be monitored can safeguard target-orientation and prevent subjectively biased data analysis.

Currently, in studies on natural forest development, one-off comparative approaches along gradients of management intensity or naturalness prevail. Contradictory results from these studies call for the scrutinizing and further improving of their methodological basis. Though we can learn a lot from comparative studies, it seems to be crucial to complement them with time-series. Thus, long-term research in SFR needs to be strengthened, particularly to make better use of the database collected. The respective results could help to streamline the extensive debates on the effects of forest use on biodiversity and the consequences of re-wilding and setting aside forests. In Lower Saxony, improving the rate of publications in peer-reviewed journals is of prior importance. The work-flow established here may be used as a blueprint to review strengths and weaknesses of other programs of SFR monitoring and research.

Monitoring is quite often not seen as a scientific task because many programs lack tractable hypothesis, an experimental design and replications (FRANKLIN et al., 1999; LINDENMAYER and LIKENS, 2010b). As designing monitoring schemes needs a scientific foundation and science benefits from long-term data, both fields of work should be regarded as complementary (FRANKLIN et al., 1999). Scientists and resource managers should intensify their cooperation significantly in designing and operating monitoring programs (LINDENMAYER and LIKENS, 2009). In respect of SFR, forest and conservation managers could be more involved in deriving research questions and in further adapting the program towards applied questions. This requires preparing and transferring results more intensively into practice and to the public.

Long-term monitoring is often considered a technical or merely scientific problem. To secure success in long-term investigations, the human dimension has to be taken into closer consideration. Humans decide to prevent subjectivity, to secure target-orientation, and to maintain necessary cooperation internally, as well as externally, between persons with different qualifications, responsibilities and viewpoints. A combination of two characteristic traits of the responsible persons seems to be essential. They have to be stubborn enough to safeguard the program even in times of a crisis, and flexible enough to adapt the program to current content-related, technical or resource requirements.

3. ABSTRACT

In Lower Saxony, Germany, research has been conducted in naturally developing strict forest reserves (SFR) for the last five decades. The intention of this study was to examine the overall scientific approach of long-term research in SFR, review the development and the strengths and weaknesses of the research program in Lower Saxony, refine the conceptual model underlying the investigations and point out key lessons for SFR research.

Long-term research in SFR follows an observational and explorative approach with the intention to capture the real world complexity of naturally developing forests. We found that two main challenges are typical: guaranteeing target-orientation and preventing subjectively biased data analysis. Because relevant scientific questions are changing in the course of time target-orientation is an intrinsic general problem of long-term research. Subjectively biased data analysis is considered to be a result of inadequate hypothesis building.

In Lower Saxony, the basic research idea was to study the main processes of tree demography and the dynamics of forest structure. The measurement protocol, the system of monitoring plots and the turnover of inventories were adapted stepwise to fit current research questions as well as staff and financial resources. As data integrity is reliable, the SFR scheme in Lower Saxony has developed into a functioning long-term program. The need for improvement is seen in scientific and applied impact.

A conceptual model of the main demographic processes and structure attributes formed the basis for the measurement protocol and helped to generate a versatile data pool. This initial model was refined (*Fig. 3*) to serve as a basis for deriving admissible hypothesis and, thus, to prevent subjectively biased data analysis.

It is concluded that long-term research in SFR, in combination with one-off comparative approaches, should be strengthened and better use should be made of the collected database. To secure success, it needs a combination of stubbornness to safeguard the program and adaptability to attune to current requirements.

4. ZUSAMMENFASSUNG

Titel des Beitrages: *Stur und anpassungsfähig – fünf Jahrzehnte Naturwaldforschung in Niedersachsen.*

In Niedersachsen werden Naturwaldreservate seit fünf Jahrzehnten untersucht. In dieser Studie werden der grundlegende Ansatz der Naturwaldforschung beleuchtet, die Entwicklung des Untersuchungsprogramms in Niedersachsen evaluiert, das konzeptionelle Modell für die Erfassungsmethodik und Hypothesenbildung weiterentwickelt und Schlussfolgerungen für die Naturwaldforschung gezogen.

Die Langfristforschung in Naturwäldern verfolgt einen beobachtend-explorativen Ansatz und ist auf die Erfassung der realen Komplexität natürlicher Waldentwicklung ausgerichtet. Grundlegende Probleme sind die Sicherung der Zielorientierung und die Vermeidung subjektiv gefärbter Datenauswertung. Da sich die wissenschaftlichen Fragestellungen im Laufe der Zeit ändern, ist die Gewährleistung der Zielorientierung ein intrinsisches Problem. Subjektivität bei der Datenanalyse geht auf unzureichende Hypothesenbildung zurück.

Das zentrale Thema in der niedersächsischen Naturwaldforschung ist die eigendynamische Entwicklung von Baumpopulationen und Waldstrukturen. Die Aufnahmemethoden, das System der Untersuchungsflächen und der Untersuchungsturnus wurden schrittweise an relevante Fragen und die personellen und finanziellen Ressourcen angepasst. Da die Datenkontinuität überwiegend aufrechterhalten werden konnte, hat sich ein funktionierendes Langfristprogramm entwickelt. Entwicklungsbedarf wird in der wissenschaftlichen und praktischen Relevanz gesehen.

Ein konzeptionelles Modell der wichtigsten demographischen Prozesse und Strukturen bildet die Ausgangsbasis für das Aufnahmeverfahren und gewährleistet den Aufbau eines vielseitig nutzbaren Datenbestandes. Das ursprüngliche Modell wurde als Grundlage für die Hypothesenbildung weiterentwickelt, um subjektiv gefärbte Datenanalysen zu vermeiden.

Es wird empfohlen, Langfristuntersuchungen in Kombination mit Vergleichsansätzen sowie die Nutzung der Datenbestände aus Naturwäldern zu stärken. Um langfristig erfolgreich zu sein, bedarf es einer Kombination von Sturheit, um das Untersuchungsprogramm zu sichern und Anpassungsfähigkeit, um es an aktuelle Anforderungen anzupassen.

5. RÉSUMÉ

Titre de l'article: *Tenace et adaptatif – cinq décennies de surveillance et de recherche sur la démographie arboricole autorégulée.*

En Basse-Saxe, des réserves forestières naturelles ont été étudiées durant cinq décennies. Dans cette présente étude, l'approche fondamentale de la recherche sur les forêts naturelles a été étudiée, le développement du programme de recherche en Basse-Saxe évalué, le modèle conceptuel pour la méthodologie d'enquête et la formation d'hypothèses ont été développés et des conclusions pour la recherche des forêts naturelles ont été tirées.

La recherche à long terme sur les forêts naturelles suit une approche observative-explorative et est orientée vers la compréhension de la complexité réelle du développement forestier naturel. Les problèmes fondamentaux consistent à assurer l'orientation des objectifs et à éviter l'exploitation subjective de données biaisées. Du fait que les questions scientifiques changent au cours du temps, la garantie de l'orientation des objectifs est un problème intrinsèque. La subjectivité dans l'analyse est due à la formation insuffisante d'hypothèses.

Le thème central dans la recherche sur les forêts naturelles de Basse-Saxe est le développement, avec une dynamique qui leur est propre, des populations d'arbres et des structures forestières. Les méthodes de collecte des données, le système des placettes de recherche et le rythme de recherche ont été progressivement adaptés à des questions pertinentes et aux ressources humaines et financières. Etant donné que la continuité des données pouvait être majoritairement maintenue, un programme sur le long terme, opérationnel, a été développé. La nécessité du développement est perçue par la pertinence scientifique et pratique.

Un modèle conceptuel des principaux processus et structures démographiques constitue le point de départ de la procédure de prise de mesures et assure la mise en place d'une base de données utilisables à des fins diverses. Le modèle d'origine a été perfectionné pour servir de base à l'élaboration d'hypothèses afin d'éviter les analyses de données subjectives et biaisées.

Il est recommandé de renforcer les recherches à long terme en combinaison avec des approches comparatives ainsi qu'avec l'utilisation des stocks de données provenant des forêts naturelles. Pour réussir à long terme, il faut combiner l'obstination à sécuriser le programme de recherche et la capacité d'adaptation aux exigences actuelles.

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