

Reforestation in Central Europe: lessons from multi-disciplinary field experiments

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Abstract

The aim of this paper is to present some lessons from multi-disciplinary, large-scale and long-term field experiments on reforestation conducted in Central Europe. The first experiment is an afforestation of a snow avalanche catchment observed during 20 years, the second consists of several case studies on windthrow areas observed during 10 to 15 years. The afforestation experiment showed a great impact of the relief on the survival and growth of planted coniferous saplings on sub-alpine sites. It promoted the use of the micro-site concept in mountain forests in general. The windthrow experiments showed a great impact of the pre-storm stand history on forest ecosystem dynamics. In both cases, the results were successfully implemented, despite difficulties to extrapolate the results to other sites and longer time periods. When designing manipulative field studies, differences in scale between sub-processes of interest should be carefully taken into account. To improve the potential for generalising results from field experiments, more use should be made of meta-analytic approaches, and of combining extensively studied field experiments with less extensive research on many areas.

Keywords: field experiments, afforestation, windthrow, forest dynamics, research methods

1 Introduction

Manipulative studies have been repeatedly used when studying the renewal of the tree layer of forest ecosystems in Central Europe. In comparison to purely observational studies, manipulative approaches have the advantage of forcing the investigator to predict desired outcomes (HAIRSTON 1989, p. 1), and thus providing a more rigid framework for scientific inference. From a management perspective, selecting among alternative treatments is often of high interest, which has promoted the application of manipulative studies in applied forest research.

Manipulative studies of forest renewal have been used for investigating plant competition (review in HAIRSTON 1989, p. 74 ff.), forest dynamics after windthrow (SCHÖNENBERGER and LÄSSIG 1995; FISCHER 1998; FISCHER and MÖSSMER 1999; BRUNNER 2002; FISCHER *et al.* 2002; SCHÖNENBERGER *et al.* 2002), regeneration of temperate mountain forests (BURSCHEL *et al.* 1985), and afforestation of high-elevation snow avalanche catchments (STERN 1965; SENN and SCHÖNENBERGER 2001). While some of these studies had a narrow disciplinary focus (e.g., BRANG 1998), others were broader in scope and involved several disciplines.

The objective of this paper is to elucidate opportunities and pitfalls of multi-disciplinary manipulative studies, based on the experience gained in studying two research topics, both related to the renewal phase of forest ecosystems in Central Europe. The two topics are the afforestation of a steep subalpine snow avalanche catchment (Section 2), and forest succession (in the sense of forest ecosystem dynamics) on windthrow areas (Section 3). In both cases, different treatments were applied, different aspects of ecosystem dynamics were studied, and system knowledge was generated and implemented to management. We will not focus on the outcome of these experiments, which is presented in detail elsewhere, but on the research design and the lessons learned for field experiments in general (Section 4).

2 Afforestation of subalpine snow avalanche catchments

2.1 Issues and research questions

The research programme was developed following catastrophic avalanches with many casualties in the Alps, in particular during the winter 1950/51. It had thus a preparation and planning time of 25 years. A number of pre-investigations preceded the main afforestation trial of 1975. Research aimed at developing cost-effective methods to afforest starting zones for snow avalanches in the subalpine belt. The site factors affecting saplings planted in subalpine afforestations, the micro-site variation, and causes for damage and mortality in afforestations were studied. Thus, the topic was clearly confined to small-scale processes.

2.2 Research approach and experimental design

On the Stillberg site near Davos (The Grisons, Switzerland), a field trial covering about 5 ha was established in 1975 (SCHÖNENBERGER and FREY 1988). This site was selected since its rugged relief and altitudinal gradient of 230 m offered a high variation of site conditions. About 92 000 saplings, 30 700 of each *Pinus mugo* Turra, *Larix decidua* Mill. and *Pinus cembra* L., were planted on square plots of 3.5 by 3.5 m arranged in a quadratic grid, with 25 saplings in each plot in regular spacing of 70 cm. From 1975 to 1995, all saplings were revisited annually to assess mortality rates. On a sub-sample of 680 plots, additional sapling parameters were recorded. A climate station has been run since 1961. Site parameters such as wind, soil temperature, solar radiation, soil type, humus form, vegetation and snow cover were assessed or interpolated for each plot, and the date and size of snow avalanches recorded each winter.

The field trial combines elements from a field experiment and a gradient study. Avalanche barriers were constructed in one half of the study site, which can be considered as an unreplicated treatment. The three species planted can also be considered as treatments. The micro-site variation created gradients of a spatial continuum, and varying weather conditions gradients of a temporal continuum.

In terms of replication, two levels should be considered: within sites, and between sites. Within the Stillberg site, the experimental unit was a plot of 25 trees. There were 4052 plots in total, and about 1350 plots for each species, assigned in a regular pattern (Fig. 1). However, the original intention was not to establish a particular experimental design suitable for testing specific hypotheses, but rather a trial with great micro-site variation suitable to stratification in the analysis.

The Stillberg site as a case study was not replicated. Two more field trials, with only a few dozens of experimental units similar to those at the Stillberg site, were established nearby in the Davos area (Lucksalp, Rudolf). However, as they exhibited no micro-site variation, and were even located on different aspects, they cannot be considered as replicates of the Stillberg field trial.

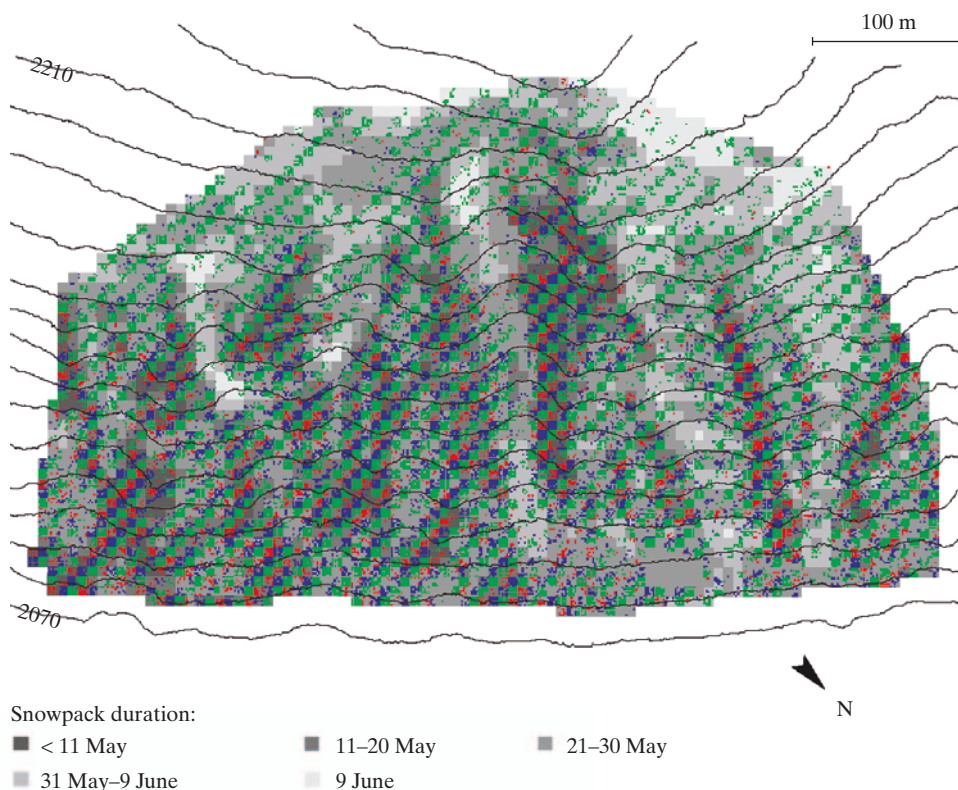


Fig. 1. Sapling survival patterns in 1995 in the Stillberg afforestation site (reproduced from SENN and SCHÖNENBERGER 2001). Red: *Pinus cembra*, blue: *Pinus mugo*, green: *Larix decidua*. In each square experimental plot, the surviving plants (out of 25 planted ones) are indicated with coloured dots. A filled square means 25 survivors, an empty square 0 survivors. Gray shading indicates average snowpack duration, from dark grey (snow free before 11 May) to light grey (snow free after 9 June).

2.3 Multi-disciplinarity

The aspects studied included tree regeneration (mortality, growth and injuries, tree physiology, root growth of planted saplings), ground vegetation (vegetation dynamics, competitive interactions), fauna, climate, soils and snow movements. The research focused on tree ecology. The disciplines involved contributed to explaining patterns found in tree development, and to establish a site classification used for stratifying sapling data.

2.4 Selected results

Sapling survival and growth were closely related to site conditions (SENN and SCHÖNENBERGER 2001). Duration of snow cover had the greatest impact on sapling survival. Survival was highest on ridges exposed to strong winds and with only short snow cover during the winter (Fig. 1). Conversely, saplings grew fastest on slopes facing south-east, which receive the highest amounts of solar radiation, are early free of snow in spring, and have, therefore, the longest growing season. Eco-physiological studies of photosynthesis, transpiration and root growth confirmed the superior sapling performance on slopes facing south-east (HÄSLER 1982; TURNER and STREULE 1985; HÄSLER 1988, 1994; KOIKE *et al.* 1994). Sapling survival and growth decreased with increasing altitude within the study area. However, the patterns differed between the three species. In particular, *Larix decidua* saplings were more able to withstand and survive extreme site conditions than *Pinus cembra* and *P. mugo* saplings.

Survival rates of the three species developed differently (Fig. 2). *Pinus cembra* had the highest survival rate during the first five years, but the lowest from the 12th to the 20th year. *Larix* had the lowest rate during the first five years, but the highest from the 6th to the 20th year. Sapling height developed similarly, with *Larix* smallest at the beginning and tallest in the 20th year. From 5- or 10-year results, it was therefore not possible to predict the pattern found after 20 years.

2.5 Generalisation

Generalisation of the results found in the Stillberg study proved to be difficult. First, some of the results were not consistent over time. In particular, the order of the three species in terms of survival (Fig. 2) and growth rates changed. Second, some pathogenic fungi (*Gremeniella abietina* [Lagerb.] Morelet, *Phacidium infestans* Karsten) were much more important in the study area than in most afforestation areas that were smaller than the Stillberg site. This may have been caused by regularly planting the saplings on a large area, which offered much potential for contagious propagation of fungi, and may thus be partly an artefact.

The vegetation type was the best indicator for predicting sapling performance on different micro-sites since it integrates all site factors over the long term. The vegetation types on slopes in other aspects or regions, however, may differ from the types found on the Stillberg site. Therefore, a primary site factor was chosen for extrapolating the micro-site concept to other sites: the pattern of snowpack disappearance. This factor has the advantage to be easily visible on any slope.

The great impact of the relief on the survival and growth of coniferous saplings found on the Stillberg site seems to hold in other sub-alpine environments where the duration of the snowpack is associated with the infection by pathogenic fungi. The study thus successfully promoted the use of the micro-site concept in mountain forests in general (AULITZKY 1965; SCHÖNENBERGER *et al.* 1990). In afforestations, the results from the Stillberg afforestation substantially contributed to giving up planting whole slopes in even spacing, and to reverting to planting seedling or sapling clusters.

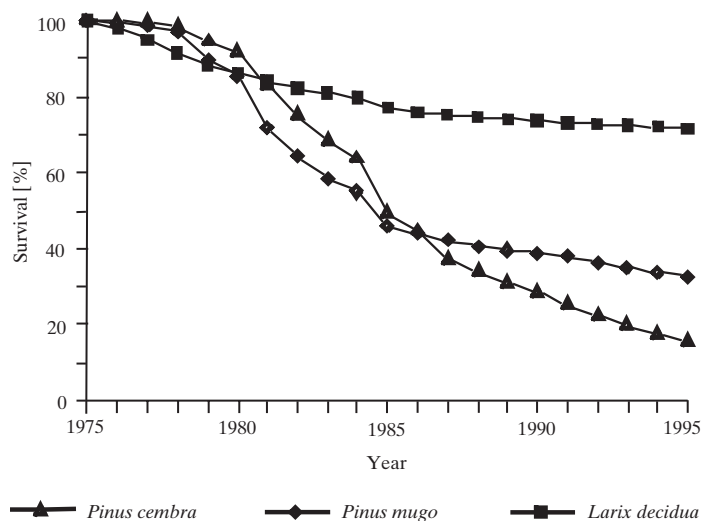


Fig. 2. Survival rates of coniferous saplings since plantation in 1975 in the Stillberg afforestation (from SENN and SCHÖNENBERGER 2001).

2.6 Implementation

The main results were communicated repeatedly (SCHÖNENBERGER 1975, 1976; TURNER and SCHÖNENBERGER 1981; TURNER *et al.* 1982; FREHNER *et al.* 1984; SCHÖNENBERGER 1985; SCHÖNENBERGER and FREY 1988; SENN *et al.* 1994; SCHÖNENBERGER and LÄSSIG 1995; FREY *et al.* 2001; SENN and SCHÖNENBERGER 2001), and implemented in comprehensive guidelines for afforestation in high altitudes (SCHÖNENBERGER *et al.* 1990). The study site was extensively used for training courses, educational units for forest managers, and yearly excursions with master students in forest sciences. The results were well received and implemented by forest managers.

However, the overall goal of the study – scientific support to afforestation of large sub-alpine avalanche catchments – became less important. Many sites prone to avalanche release have regained forest cover, or were made safe by avalanche defense constructions (AMMANN 2000). The annual afforestation area in the Swiss Alps dropped considerably from about 500 ha in the period 1985–1994 to less than 100 ha since (KISTLER 2003).

3 Forest dynamics after windthrow

3.1 Issues and research questions

Several severe winter storms of hitherto unknown extent hit central Europe in the last 20 years, including the hurricanes Vivian and Wiebke in February 1990, and Lothar and Martin in December 1999. As the interest in natural forest dynamics and pressure to reduce management costs increased, traditional approaches to manage windthrow areas were questioned.

The main issues were whether fallen logs should be harvested or could be left on site, and whether natural regeneration should be replenished with planting. In particular, in 1990, there was no management experience with leaving timber unharvested, despite a study which started in 1988 in the Bavarian National Park. It was, therefore, difficult to predict how leaving timber would affect tree seedlings (defined here as trees <20 cm) and saplings (>20 cm), competitive interactions among young trees and the herb layer, plant, animal and fungal biodiversity, soil development, surface erosion and natural hazards.

3.2 Research approach and experimental design

Research started soon after the storms occurred in 1990. The study sites and treatments were determined within a few months, the study design within less than a year after the storm. There was no time for long debates on the design if missing the first phase of forest renewal was to be avoided. Research topics and projects partly depended on the immediate availability of qualified scientists. There was no cross-border international co-ordination.

Manipulative field experiments and permanent observation sites were set up, among others, in Bavaria, Baden-Württemberg, Rheinland-Pfalz, Hessen, and Switzerland (Table 1). Treatments varied among sites, but often included i) leaving a windthrow area uncleared, ii) clearing, and iii) clearing and planting. In Baden-Württemberg and Rheinland-Pfalz, several planting treatments were used. In some sites, treatments were applied as part of the study, in others, areas treated in different ways were assigned to treatments in retrospect. A contiguous area receiving the same treatment is, in a statistical sense, the experimental unit. In contrast, plots within each experimental unit are similar, and cannot be considered as true replicates.

Additional sites, which were left to natural succession, were selected for long-term observation in Switzerland in order to get, in addition to the information from extensively studied manipulative field experiments, a more representative picture of forest succession after windthrow (SCHÖNENBERGER and LÄSSIG 1995). More experiments and study sites were established after the hurricanes in winter 1999 (e.g., BRUNNER 2002), but will not be presented here since the results are only very preliminary so far.

The study sites were selected based on different criteria, e.g. in Switzerland, i) steep slopes prone to natural hazards, ii) co-operation of the forest owners and forest service, iii) feasibility of three adjacent clearing and planting treatments. Most of the sites have been monitored periodically since, sometimes with increasing time intervals, mostly using repeated measurements with plots located in systematic grids (Table 2). Disciplines used a wide variety of monitoring approaches corresponding to the spatial and temporal scales of the processes studied. After about one decade of observation, modelling forest succession was used to get a deeper understanding of processes on windthrow areas (FISCHER *et al.* 2002).

Due to financial and feasibility restrictions, treatments were usually not replicated within a site (but see HUSS 2002). Therefore, in cases where several sites were investigated, treatment and site effects can not be isolated. In Bavaria seven study sites (out of ten) were established to analyse forest dynamics on former *Picea abies* (L.) Karst. sites. These seven sites are distributed all over Bavaria which is why each site exhibits specific site conditions. Plots within a site, and within a treatment, are not independent replicates.

Table 1. Field studies on forest dynamics on windthrow areas.

Country	Number of sites	Altitude a.s.l. (m)	Treatments	Topics studied	Time period of study	Main reference
Bavaria	10	360–840 (1410)	Cleared, uncleared, cleared + planted	Stand development, ground vegetation	1991–2000	MÖSSMER and FISCHER 1999
Bavarian National Park	2	750	Cleared, uncleared	Stand development, ground vegetation	1988–2003	FISCHER <i>et al.</i> 2002; JEHL 1995
Nordrhein-Westfalen	4	210–375	Uncleared (cleared+planted)	Stand development, ground vegetation	1991–2000	LEDER and KRUMNACKER 1998
Rheinland-Pfalz	2	390–456	Cleared, cleared + planted	Stand development, ground vegetation, water balance, micro-climate	1991–2000?	HUSS 2002
Baden-Württemberg	3	535–560	Cleared, uncleared	Site conditions, stand development, ground vegetation, fauna, fungi	1990–1998	FISCHER 1998
Hessen	1	310–410	Uncleared	Site conditions, stand development, ground vegetation, fauna	1990–1998	WILLIG 2002
Switzerland	3 (4)	900–1560	Cleared, uncleared, cleared + planted	Site conditions, stand development, ground vegetation, fauna, natural hazards	1991–2000	SCHÖNENBERGER <i>et al.</i> 2002

Table 2. Research topics and sampling design used on windthrow areas in Switzerland. The design is mostly repeated in every experimental unit (treatment).

Research topic	Sampling design	Temporal scale
Soil	2–4 soil profiles in each microsite type	Every 5 years
Vegetation	20–40 permanent plots of 1 m ² , stratified by microsite types and whole area mapping	First yearly, later every 5 years
Tree seeds	10–20 seed traps in vertical and horizontal transects	Monthly in seed years
Tree seedlings <20 cm	20–40 permanent plots of 1 m ² , stratified by site types	First yearly, later every 5 years
Tree saplings >20 cm	25 permanent plots of 50 m ² , arranged in a quadratic grid of 20 m mesh width	First yearly, later every 5 years
Insects	1 window and 1 surface trap	During two years at the beginning, later reduced monitoring intensity
Ungulate browsing	1 fenced enclosure and control area	3 years
Avalanches	Mapping of avalanche release and transit in whole area	After each event
Surface erosion	Mapping of erosion scars in whole area	Year 1 and 10
Wood decay	Single logs	Year 10

3.3 Multi-disciplinarity

Scientists of different disciplines generally used the same study sites, but not every discipline was represented in each site. Within a study site, several disciplinary studies used the same area. The results thus refer to the same areas. In some sites, e.g. in the Swiss sites, basic site information was made accessible to all scientists. It included a site description, information on stand history, terrestrial and aerial photographs, detailed site maps, and terrain models established using GIS methods. Moreover, paths were constructed.

For data analysis, most disciplines used only own data, apart from data used to stratify the site. Attempts to explain patterns found in one discipline by data generated by other disciplines were rare. However, co-operation during field work, common extension activities, workshops and some publications with multi-disciplinary authorship established numerous personal links.

3.4 Selected results

Only selected results from studies initiated after the storms “Vivian” and “Wiebke” in 1990 can be presented here. In general, few patterns were consistent between all sites. In areas where intensive human impact had occurred during several centuries, pioneer herbs were present in the pre-storm stand, or their diaspores had accumulated in the soil. This caused a fast development of these herbs after the storms. In other areas with less extensive human impact, pioneer herbs reached only loose cover (FISCHER *et al.* 1998).

On many areas, advance regeneration that had established before the storm had for many years a higher density than post-storm regeneration (e.g., FISCHER *et al.* 1998; Fig. 3 for the

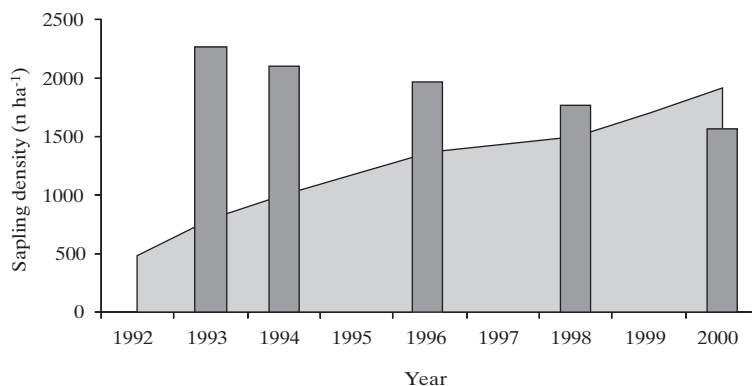


Fig. 3. Development of sapling density in the planted treatment of the Schwanden site, Switzerland. Curves (areas) represent saplings from natural regeneration, columns planted saplings. Source: SCHÖNENBERGER (2002).

Schwanden site). In some areas, however, advance regeneration was sparse when the storms occurred, or destroyed by logging operations. On many windthrow areas, the proportion of broadleaves was much higher in natural regeneration than in planted saplings, and also higher than in the pre-storm stand.

While trees established quickly on most lowland storm areas, regeneration in some sites in higher altitudes is still sparse after ten years, and even so sparse that a prediction when it will offer effective protection against natural hazards is not possible (SCHÖNENBERGER 2002). In mountain areas, saplings from natural regeneration reached the same density as planted saplings ($1500\text{--}2500\text{ ha}^{-1}$) only after about 10 years, despite 20 to 30% mortality in planted saplings (Fig. 3). Moreover, planted saplings were taller than those from natural regeneration. This means the planted treatment was 10 years ahead with regard to reforestation.

The species composition of fungi, the ground vegetation and insects often differed between treatments. The highest species richness was reached within areas that had received different treatments. The logs left on uncleared treatments effectively prevented rockfall and avalanche release on steep slopes.

3.5 Generalisation

Based on monitoring results, the studies enabled quantification of various aspects of forest dynamics on windthrow areas, e.g. species composition of trees and the ground vegetation, and rates of seedling establishment and mortality. Knowing these rates is important for decision-making in managing windthrow areas, although rates derived from case studies cannot be generalised, and applied to other areas, without precaution.

Treatments generally represented management options, and were therefore not designed to differentiate between conflicting hypotheses related to an ecological question. The treatment impact on ecological processes such as seed germination, seedling establishment and competitive interactions was often obvious, although it differed between sites. However, the case study design with no within-site replications made it difficult to establish statistical significance for treatment effects. We are not aware of an attempt to combine selected results

from all sites in a meta-analysis (GUREVITCH and HEDGES 1993; HASSELBLAD 1994; PETERSON *et al.* 1999).

The influence of other factors than treatments, such as seed dispersal or climatic extremes, on forest development was inferred from patterns found in monitoring results. Since the design was inefficient to detect such influences, only weak inference about driving factors was possible.

Some treatment effects were found on many sites, and seem to be generally valid. First, logging windthrown timber destroyed considerable amounts of advance regeneration, but promoted seedling establishment on disturbed micro-sites. Second, the windthrow disturbance initiated the fast development of herbaceous vegetation and shrubs from the soil seed bank, in particular in forests with a long history of human disturbance. Third, treatments affected plant and insect diversity. Combining different treatments in a catchment, in particular logging and leaving windthrown timber, lead to highest diversity.

3.6 Implementation

Windthrow research had an extremely abrupt start with the hurricanes “Vivian” and “Wiebke” as a trigger and experienced a spectacular revival through the hurricanes “Lothar” and “Martin” ten years later. Results were published continuously, including a number of special issues of journals (SCHÖNENBERGER and LÄSSIG 1995; FISCHER 1996; FISCHER 1998; HEURICH 2001; SCHÖNENBERGER *et al.* 1995 and 2002). An exemplary and well co-ordinated implementation project was the elaboration of guidelines for managing windthrow events in mountain forests (BUWAL 2000), co-ordinated by the Swiss Forest Agency and supported by a working group of forest managers, scientists, and other stakeholders such as conservationists, forest owners, hunters etc. These guidelines are based on research results and management experience gained during the first five years after “Vivian”. In a number of training courses, managers learned how to use them. The guidelines can be refined to take increasing knowledge into account. In Bavaria, reforestation guidelines for private forest owners were published (SCHÖLCH *et al.* 2002). Several other publications aimed at implementing research results into management (SCHÖNENBERGER and RÜSCH 1990; HUSS and HEHN 2000; SCHÖNENBERGER *et al.* 2003).

Besides publications, the scientists and forest services offered numerous guided tours, excursions, lectures, newspaper articles and radio and television interviews to a multifaceted public. These activities were intended to increase public awareness and understanding of the ecology and management of windthrow areas, and to demonstrate how research can support management. The study sites thus became well known to the scientific community and to the public.

4 Critical appraisal of the approaches used

4.1 Introductory note

The statements in this section are meant as a contribution to more effective and efficient field experiments in the future, by learning from the experience gained in high-elevation afforestation experiments and on windthrow areas during several decades. Any critique stated does not imply that the inference of this ex-post appraisal was foreseeable when the experiments were established.

4.2 Experimental design

In both cases, afforestation of snow avalanche catchments and forest succession after windthrow, the field studies were established on areas similar in size to those treated in management operations. Afforestations of avalanche catchments, for instance, traditionally cover whole slopes without any gaps, similar to the Stillberg afforestation. However, an area would certainly not have been split into small and evenly sized experimental plots of 3.5 x 3.5 m. These small plots were selected in the study to represent single micro-sites, with small within-plot variation of environmental conditions. This aim was reached. A potential artefact of the regularly spaced planting scheme was an enhanced spread of pathogenic fungi, although this is often a problem in large-scale afforestations, too. From a methodological viewpoint, it is questionable whether the high number of experimental units was necessary to sufficiently cover the environmental gradients on the site. The response of the three species to micro-sites could have been investigated with a smaller number of experimental units.

In the windthrow areas with planned or retrospectively selected treatments, the size of each experimental unit (= treatment) was much larger than in the Stillberg study, up to 3 ha. This large area caused considerable within-unit variation, which seems inevitable in a treatment reflecting operational scales. Convincing a forest owner to establish replicates within a site would have been difficult, apart from increased edge effects in smaller experimental units. At that time, leaving an area uncleared was already sufficiently novel, or even strange.

HAIRSTON (1989, p. 58) states: "Anyone who has engaged in field experimentation will appreciate the danger of loss of statistical significance from the loss of replicates per treatment". In the afforestation study, the site remained unreplicated. In the windthrow studies, sites were often replicated, but these replicates are different case studies and not replicates in a statistical sense. Moreover, there was usually no within-site replication of the treatments. At least, these studies could not be "analyzed under the assumption that sub-samples can be regarded as replicates" (EBERHARDT and THOMAS 1991).

Establishing meaningful replicates seems almost impossible in field experiments where an experimental unit covers several hectares since site conditions vary at a small scale within each block or even experimental unit (RIEK and STROHBACH 2001), in particular in rugged mountain terrain. The drawbacks of unreplicated experiments are discussed by EBERHARDT and THOMAS (1991). According to them, "progress is actually made through sequences of investigations", i.e. a series of related studies.

4.3 Scales of monitoring

Forest renewal is a complex process which consists of a number of sub-processes such as seed production and dispersal, germination, seedling establishment, sapling growth and mortality and competitive interactions. Different factors and processes may operate at markedly different spatial and temporal scales. Extremes acting during short time periods are often highly influential. Research must respect this, and select an appropriate approach for each sub-process. For instance, germination takes a few weeks only, may be influenced by meteorological phenomena such as rain splash or lethal surface temperatures, which act for a few minutes only, and depends on specific micro-site conditions which vary on a scale of a few decimetres. This process cannot be studied with yearly observations only. Different disciplines did therefore not use the same frequency and extent of monitoring, in both afforestation and windthrow studies. For instance, root temperatures of selected trees in the Stillberg site were measured every five minutes (TURNER and STREULE 1983), and sapling mortality yearly (SENN and SCHÖNENBERGER 2001).

In both the afforestation and the windthrow studies, the general monitoring approach with annual to five-year surveys was appropriate for assessing quantitatively the succession of the ground vegetation and sapling growth and mortality. For detecting the relative influence of different factors on forest dynamics, however, more frequent observations during phases with high rates of change would have been required. For instance, pathogenic fungi in the Stillberg develop during a few weeks in winters with a long-lasting snowpack, and seedlings on windthrow areas may be browsed during a few days only.

The intensity of monitoring decreased in both the Stillberg and windthrow studies. Time intervals between surveys increased from one to five years, and a full sampling was often replaced with sampling only parts of the plots established in the beginning. This reflected first the expectation that the system knowledge would not grow with more data on patterns already detected and second with decreasing rates of change. However, the long duration of monitoring (20 years in the Stillberg afforestation until now) is needed. From 5- or 10-year results on seedling survival, it was not possible to predict the pattern found after 20 years. Therefore, long-term research is needed for many longitudinal studies.

Initially, the number of trees within each experimental unit (Stillberg) and of plots within each experimental unit (windthrow areas) was to our knowledge not chosen based on a pilot study to assess the variation, and the accuracy needed, but rather on the resources available. These aspects need more consideration when planning future field experiments.

Artefacts can be a problem in repeated monitoring. Consecutive surveys of the same plots have disturbed the ground vegetation, and thus influenced the results to an unknown extent. Competitive effects of the ground vegetation on seedlings and saplings have probably been underestimated in both afforestation and windthrow studies.

4.4 Multi-disciplinarity

Researchers of different disciplines communicated and learned from each other more in the Stillberg study than in the windthrow studies. The reason is the narrower focus of the first study on trees. The disciplines were all working to explain aspects related to tree saplings, and therefore closely linked. In the windthrow studies, not all aspects were closely linked through ecological processes. Scientists of different disciplines came with a different view (mental model) of the elements and processes relevant for windthrow succession, and even with different value systems. For instance, from a traditional forest management viewpoint, tree establishment and growth are most important, and ground vegetation is rather perceived as a problem. From a conservation viewpoint, competitive effects of the ground vegetation on trees are of secondary importance, but plant, fungal, and insect diversity of primary interest. Therefore, different disciplines used the same study sites, but the links between disciplines were weak. In the case of the windthrow studies, it is therefore more appropriate to call the co-operation between disciplines “multi-disciplinarity” than “inter-disciplinarity”. From these experiences, we conclude that the challenge of cooperating between disciplines and mutual learning increases with the number and diversity of disciplines involved.

In all studies, every discipline managed its own data. There was no common database, except for detailed maps and GIS models for each study site. Depending on the affiliation of the scientists involved, data were and remain stored in different research institutions.

4.5 Process knowledge generated

In the afforestation experiment, additional studies enabled to understand the patterns found in the field experiment. Microclimatic and eco-physiological studies, coupled with mapping snow accumulation and melt patterns, enabled an understanding of the performance of saplings on different micro-sites, and in different years. Studying the behaviour of pathogenic fungi enabled an understanding of their important role in a regularly spaced afforestation.

On the windthrow areas, understanding processes and driving factors was more difficult, and the patterns were more complex. An important reason for this is that all saplings were planted in the afforestation experiment, while most saplings were from natural regeneration in the windthrow areas. Deriving the underlying processes of advance regeneration, seed dispersal, seed germination and seedling establishment retrospectively from established seedlings and saplings was only partly possible. Another reason is the strong environmental gradient in the afforestation, from micro-sites amenable to sapling growth to micro-sites adverse to saplings. The gradients on windthrow areas were much more gentle, and did certainly not include micro-sites where trees are generally unlikely to establish and to survive.

It is interesting to note that the understanding of ecological processes was to a considerable extent generated by additional studies, and not by monitoring the response of the objects of interest to the treatments alone. Monitoring intervals were not for all processes sufficiently short to enable identification of factors which caused relevant changes such as tree death. In particular in forest succession after windthrow, the observational approach reflected insufficient system knowledge when the studies started. Studies in which it was attempted to understand processes and causal relationships were initiated only later. This should be considered when planning a field experiment. It should be possible to integrate detailed studies of selected sub-systems once unexplained patterns emerge.

4.6 Generalisation

HAIRSTON (1989, p. 65) nicely outlines the problems encountered when assessing the general validity of results from field experiments: "... the hypothesis ... generated usually can be tested experimentally in only one place. A successful outcome gives confidence in the hypothesis, but the confidence may not be extendable to other areas." This is particularly true in mountain terrain where site conditions vary greatly across altitudinal and climatic gradients, different aspects, and different bedrock. However, in the case of windthrow research, these difficulties in generalisation of research results are coupled with barriers due to insufficient replication within and between the case studies.

The Stillberg study contributed to promoting the micro-site concept in research and management related to mountain forests. The concept states that ecological conditions may vary considerably at very short distances. These variations may be decisive for ecological processes such as seed germination or seedling mortality. The micro-site concept (AULITZKY 1965; SCHÖNENBERGER *et al.* 1990; BRANG 1997), and the related cluster afforestation concept developed from the Stillberg experiment (SCHÖNENBERGER 2001), were fruitful for artificial and natural regeneration of mountain forests in general. This generalisation was not planned when the afforestation experiment started in 1975.

4.7 Implementation

Guidelines for management decisions were issued from both the afforestation and the windthrow studies. Research supported managers by giving clear general advice what to observe and to consider in decision-making. However, the guidelines also emphasised the necessity to take local knowledge and observations into account.

Two highly effective ways of communicating research results should be highlighted: The elaboration of guidelines with stakeholder groups, and training courses in the field. These activities seem to foster the necessary “trust” in research results among forest managers. Written material is useful to convey information, but managers do not necessarily have sufficient confidence in it (PREGERNIG 2002). In Switzerland, the forest management community, and not scientists, took the initiative to elaborate the guidelines. This facilitated their implementation.

In research on windthrow areas, the interest of the public was remarkable, and led to numerous extension activities. One reason is the spectacular trigger of this research, the hurricanes and their destructive effects not only on forests, but on infrastructures as well, which caught the attention of people and the media.

Implementation activities were usually not planned when research started. This is not a problem if researchers generally agree that implementation is important, and are generally willing to contribute to it. However, in windthrow research, more co-ordination between the research institutions involved would have been desirable in both research design and implementation. There were some implementation links between the institutions, but they consisted mainly in mutual contributions to workshops.

5 Recommendations

We have presented two cases of field experiments in this paper, afforestation of snow avalanche catchments and forest dynamics after windthrow. From the experience gained, a few general conclusions can be drawn, and recommendations given.

Field experiments at the scale of management operations have several advantages over other approaches in forest research, but also some drawbacks. It is important to be aware of these advantages and drawbacks when designing field experiments. Among the advantages, we would like to mention: i) the possibility to assess processes and factors which are relevant for system dynamics, but unknown at the beginning, in particular in comparison to laboratory experiments; ii) a better knowledge of stand development and often even initial conditions and some causal relationships, in comparison to purely retrospective approaches; iii) a great potential for effective extension at the study site. The drawbacks include i) problems with extrapolating the results to other sites (although these problems may be smaller than with laboratory experiments), ii) a considerable investment of resources, and iii) the necessity of a long-term commitment.

From our experience with field experiments, several suggestions can be made. First, it is important to respect differences in scale. For each process, an adequate monitoring resolution in space and time should be used.

Second, care is needed when generalising results from field experiments. Extrapolating results to other sites may be hampered by differences in site conditions. Extrapolating results for longer time periods may fail since linearity is, for many ecological phenomena, not a plausible assumption, and patterns found after some years may be reversed later (Fig. 2).

Moreover, the results of a field experiment can only be reproduced to a certain extent since many factors, including weather conditions, are not under control.

Third, when planning a large-scale field experiment, we advocate considering the establishment of additional sites with less detailed observation. This can greatly improve the ability to extrapolate the results of the experiment. Moreover, since forest managers tend to rely more on their local management experience than on research results from remote sites, local trials are valuable in extension activities.

Forth, meta-analytic approaches (GUREVITCH and HEDGES 1993; HASSELBLAD 1994), which combine the results from several studies to increase the inference possible, should be considered when planning large-scale field experiments. To our knowledge, this approach has not been used to analyse the data from afforestation of avalanche catchments and forest succession after windthrow. In the latter case, where about 25 case studies are available, this approach seems particularly promising, although the site conditions, the pre-storm stand history and the observation period vary between sites.

To study afforestation of avalanche catchments and forest succession after windthrow, long-term field experiments have been established 10 to 28 years ago. These experiments have required considerable investments, but also substantially contributed to guidelines useful in decision-making. New approaches to investigate forest dynamics, in particular simulation models, may enhance our understanding, but they cannot replace longitudinal studies. In the opposite, they depend on reliable data from long-term field studies.

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6 References

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