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Dr. K.-R. Volz
o. Professor
der Forstwissenschaft an der
Universität Freiburg i. Br.

Dr. Dr. h.c. K. von Gadow
o. Professor
der Forstwissenschaft an der
Universität Göttingen

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Die Anschriften der Herausgeber:

Prof. Dr. K.-R. VOLZ, Institut für Forst- und Umweltpolitik der Universität Freiburg, Tennenbacher Str. 4, D-79106 Freiburg

Prof. Dr. Dr. h. c. KLAUS VON GADOW, Institut für Waldinventur und Waldwachstum der Universität Göttingen, Büsgenweg 5, D-37077 Göttingen

Addresses of the corresponding authors:

LISA M. GANIO, Department of Forest Science, Oregon State University, Corvallis, OR 97331, USA.
E-Mail: lisa.ganio@oregonstate.edu

JOHN E. HICKEY, Forestry Tasmania, Australia.
E-Mail: john.hickey@forestrytas.com.au

DOUGLAS A. MAGUIRE, Department of Forest Science, Oregon State University, Corvallis, OR 97331, USA.
E-Mail: Doug.Maguire@orst.edu

CHARLES E. PETERSON, U.S. Department of Agriculture, U.S. Forest Service, Pacific Northwest Research Station, 620 SW Main St, Suite 400, Portland, OR 97205, USA.
E-Mail: cepeterson@fs.fed.us

ROBERT S. SEYMOUR, University of Maine, Orono, ME 04469, USA.
E-Mail: Seymour@umenfa.maine.edu

ROBERT C. SZARO, U.S. Department of Interior, U.S. Geological Survey, 12202 Sunrise Valley Drive, MS 300, Reston, VA 20192, USA.
E-Mail: rszaro@usgs.gov

Übersetzung der Résumés,
soweit sie nicht von den Autoren zur Verfügung gestellt werden:
J. MAHEUT, 25 Av. du Gal Leclerc, F-54600 Villers-les-Nancy

VORWORT – FOREWORD

Disziplinübergreifende Feldversuche bilden die Grundlage für eine nachhaltige Waldnutzung auf wissenschaftlicher Basis

Gast Editoren: Charles E. Peterson[1]), Robert C. Szaro[2])

Neuartige forstliche Feldversuche, die zur Beantwortung komplexer ökologischer und ökonomischer Fragestellungen beitragen können, gewinnen überall auf der Welt an Bedeutung. Daher haben sich einige Mitglieder im IUFRO Exekutivkomitee während einer Tagung in Nord Amerika im Sommer 2002 besonders für die großflächigen waldbaulichen Feldversuche im Pazifischen Nordwesten der USA interessiert. In der Folge wurde ein erstes Arbeitstreffen in Davos/Schweiz und ein zweites in Portland/Oregon, USA, durch die IUFRO Sektionen 1 und 4 organisiert. Während dieser zwei Workshops wurden Themenbereiche für den IUFRO Weltkongress 2005 identifiziert, die sich mit großflächigen, interdisziplinär angelegten forstlichen Feldversuchen befassen.

Relevante Beiträge wurden im Rahmen der internationalen Workshops in Davos und Portland zusammengestellt und später veröffentlicht (**Davos:** s. Sonderausgabe 2003 der Zeitschrift *Forest Snow and Landscape Research, Vol 78* (1/2); **Portland:** s. Peterson, C. E. u. Maguire, D. A., 2004 (Hrsg.): Balancing Ecosystem Values – Innovative Experiments for Sustainable Forestry. Proceedings of a conference. General Technical Report PNW-GTR-635, Portland, Oregon, US Dept of Agriculture, Forest Service, Pacific Northwest Research Station: 389 S). Diese Veröffentlichungen fassen die wichtigsten Herausforderungen und Erfahrungen im Zusammenhang mit Design und Implementierung von großflächigen Feldversuchen zusammen, deren Ziel darin besteht, die Reaktionsmuster auf unterschiedliche forstliche Eingriffe zu erfassen.

In der Vergangenheit haben waldbauliche Feldversuche sich vor allem mit Fragestellungen der Holzproduktion befasst. Während dieses Thema im Privatwald stets wichtig ist, ergeben sich andere Prioritäten in öffentlichen Wäldern und Naturlandschaften. Dort wird ein umfassendes Management unter gleichzeitiger Einbeziehung sozialer, ökologischer und ökonomischer Zielsetzungen gefordert. Daher sind zahlreiche waldbauliche Feldversuche multidisziplinär und oft großflächig angelegt. Diese Versuchsanlagen erfordern teilweise erhebliche Investitionen durch Forschung und Verwaltung. Letztendlich ist das Ziel die Befriedigung der Nachfrage nach Wäldern, die eine gesunde Natur für die Stadtbevölkerung, eine hohe Biodiversität und Habitatvielfalt, nachhaltige Produkterträge und langfristig gesicherte Arbeitsplätze bieten können. Langfristig angelegte waldökologische Feldversuche erweitern die wissenschaftliche Basis für die methodische Weiterentwicklung der nachhaltigen Waldnutzung. Sie erleichtern den Transfer wissenschaftlicher Erkenntnisse in die Praxis und verbessern den Austausch zwischen Wissenschaft und Politik.

Dieses Themenheft der *Allgemeinen Forst und Jagdzeitung* umfasst fünf Beiträge, die im Jahr 2005 während der IUFRO Weltkonferenz präsentiert wurden und bildet damit die dritte Phase einer mehr umfassenden IUFRO Initiative zur Darstellung forstlicher Feldversuche in Nordamerika, Europa und Asien. Einige dieser Experimente sind erst unlängst angelegt und daher noch relativ unbekannt.

Der Beitrag von Szaro *et al.* zeigt den dramatischen Wandel der öffentlichen Meinung in Bezug auf die erwünschte Waldnutzung und die entsprechende Ausgestaltung der Forschungskontexte, und beschreibt Ansätze zur Verbesserung von Entscheidungen auf der Basis von disziplinübergreifenden Feldversuchen. Der Artikel von Seymour *et al.* vermittelt einen Überblick über langfristig angelegte Feldversuche in vier gemäßigten Regionen der Vereinigten Staaten, in denen jeder der Ko-Autoren eine wichtige regionale Funktion ausübt. Maguire *et al.* beschreiben etwas detaillierter die Struktur und Funktion eines multi-disziplinären Großprojektes mit alternativen Waldbauverfahren im Nordwesten der USA. Ein Beispiel wird in dem Beitrag von Hickey *et al.* vorgestellt, dabei handelt es sich um ein Großexperiment in einem Eucalyptus Feuchtwald in Tasmanien. Dieser Feldversuch ist Teil eines weltweiten Netzwerkes ökologischer Untersuchungen. Ganio schliesslich demonstriert die Bedeutung der Planung von Feldversuchen und zeigt, wie Replikation, Randomisierung und die zeitliche Planung der Aufnahmen die Genauigkeit, den Bias und die statistische Aussage beeinflussen.

[1]) U.S. Department of Agriculture, U.S. Forest Service, Pacific Northwest Research Station, 620 SW Main St, Suite 400, Portland, OR 97205, USA. E-mail: cepeterson@fs.fed.us

[2]) U.S. Department of Interior, U.S. Geological Survey, 12201 Sunrise Valley Drive, MS 300, Reston, VA 20192, USA. E-mail: rszaro@usgs.gov

Building a Foundation for Sustainable Science-based Forest Management: Long-term multi-purpose experiments in the forest sector

Guest Editors: Charles E. Peterson[1]), Robert C. Szaro[2])

There has been a growing need to design new types of field experiments that would address the complex set of ecological and socio-economic objectives in sustainable forest management. Members of the IUFRO executive board, while meeting in North America during the summer of 2002, became interested in the large-scale field studies conducted in the Pacific North-West forestry region. A first workshop in Davos/Switzerland and a second one in Portland/Oregon, convened by IUFRO's Divisions 1 and 4, helped to identify important themes for the 2005 IUFRO World Congress, focusing on large-scale interdisciplinary field experiments for sustainable forestry.

A range of relevant papers were presented in Davos in 2003 (refer to a Special Issue of *Forest Snow and Landscape Research,*

[1]) U.S. Department of Agriculture, U.S. Forest Service, Pacific Northwest Research Station, 620 SW Main St, Suite 400, Portland, OR 97205, USA. E-mail: cepeterson@fs.fed.us

[2]) U.S. Department of Interior, U.S. Geological Survey, 12201 Sunrise Valley Drive, MS 300, Reston, VA 20192, USA. E-mail: rszaro@usgs.gov

Vol 78 (1/2)) and 2004 (refer to PETERSON, C. E. and MAGUIRE, D. A., 2004 (eds.): Balancing Ecosystem Values – Innovative Experiments for Sustainable Forestry. Proceedings of a conference. General Technical Report PNW-GTR-635, Portland, Oregon, US Dept of Agriculture, Forest Service, Pacific Northwest Research Station: 389 p) summarized the important challenges and lessons learned from designing, implementing and maintaining experiments at an operational scale that test ecological, social, or economic responses to silvicultural treatments.

Past silvicultural studies have evaluated specific treatments with primary emphasis on wood production. Whereas wood production remains an important economic objective for private and non-industrial landowners, changing societal values for federally managed forests and rangelands now demand more comprehensive approaches to forest management that integrate social, ecological, and economic goals, ideally as joint production functions. As a result, many recent (past decade) silvicultural experiments have become multi-disciplinary in scope and include restorative objectives, novel and untested silvicultural treatments, or traditional approaches expanded to operational scales. Individually and collectively, these long term studies represent major investments by research and land management organizations and the ultimate objective is to meet increasing public demands for forests that provide a healthy environment for urban people, a biologically diverse structure and composition for habitat, sustainable yields of forest products and long-term job opportunities. Applied long-term forest ecological experiments greatly enhance the scientific basis for the advancement of sustainable forest management. They also help facilitate the transfer of scientific results into practical applications and to realize a more effective interface between science and policy.

This special issue of the Allgemeine Forst und Jagdzeitung includes five papers that were presented at the 2005 IUFRO congress, representing the third phase of a more comprehensive IUFRO effort to highlight examples of operational-scale experiments from North America, Europe, and Asia. Some of these field experiments are in the early stages of implementation and are thus still relatively unknown.

SZARO *et al.* was a significant address to the congress sub plenary that speaks to the dramatic shift in public perspective on how forests should be managed, the basic interactions that help define the research context, and how new integrative forest research experiments will greatly improve decision-making in policy and management. The paper by SEYMOUR *et al.* provides a broad view of the long term silviculture experiments ongoing in the four major temperate regions of the United States, where each of the co-authors plays a major regional role. MAGUIRE *et al.* offer an in-depth look at the first major multi-disciplinary experiment intensively designed to evaluate variable retention harvests that achieve ecosystem management goals. In contrast, HICKEY *et al.* provide an example of long-term research of wet eucalypt forests in southeast Australia. This particular study, though not widely replicated, is part of a global network of ecological experiments. Finally, GANIO challenges the scientists to define and prioritize their primary statistical objectives that drive the study design and also to more readily take advantage of the experimental design phase of a study to assess how various choices for replication, randomization and the temporal considerations affect precision, bias and statistical inference.

Operational Experiments for Sustainably Managing Forests

(With 1 Figure and 1 Table)

By R. C. SZARO[1)], C. E. PETERSON[2)] and K. VON GADOW[3)]

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1. ABSTRACT

Historically, applied manipulative studies of forests have tested the ability of specific silvicultural treatments to address wood production objectives. Changing societal values now demand expanded approaches to forest management that also integrate social, ecological, and economic goals. As a result, many recent (past decade) experimental manipulations have become multi-disciplinary in scope and approach and involve restorative treatments, novel silvicultural approaches or variants of more traditional approaches that are relevant to operational scales. We examine a wide range of manipulative forest ecological experiments that have addressed a variety of responses to changes in forest structure or function. The silvicultural treatments employed in these experiments were oftentimes designed by interdisciplinary teams (e.g., forest ecologists, sociologists, biologists, economists, and silviculturists) with wood production and additional ecological, social or economic objectives as joint outcomes. Individually and collectively these studies represent major investments by research and land management organizations to meet increasing public demands for forests that provide healthy environments for people (clean air and water), support biological diversity (e.g., habitat), and sustain economic productivity (wood or other forest products and jobs).

2. INTRODUCTION

Forests represent a global resource and many issues dealing with their use and maintenance cannot be effectively dealt with in an

[1)] U.S. Department of Interior, U.S. Geological Survey, 12201 Sunrise Valley Drive, MS 300, Reston, VA 20192, USA. E-Mail: rszaro@usgs.gov

[2)] USDA Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, 620 SW Main St, Suite 400, Portland, OR 97205, USA.

[3)] Institute of Forest Management; Georg-August-University Göttingen, Büsgenweg 5, D-37077 Göttingen, Germany.

insular fashion (SZARO, 2000). Global participation is desirable, and often considered even mandatory, if these resources are to be sustained and equitably utilized. This approach must ensure that forests will continue to exist at some acceptable level for the benefit of current and future generations. Attempts to meet this objective are often referred to as "sustainable forest management". Sustainability requires the integration of environmental, social and economic aspects through compatible management and development strategies (LOSKILL, 2006). The German Council for Sustainable Development (RAT FÜR NACHHALTIGE ENTWICKLUNG, 2004) highlighted the needed link between forestry and forest research in order to transfer the knowledge gained from centuries of management experience and recent developments in forest modeling to implement the differing facets of sustainability in novel societal approaches. This recognizes that managing a forest ecosystem is a complex and challenging task, because it is necessary to value the system as a whole. This involves treating all the functions simultaneously and often as equally important or at least finding a balance between them. This challenge is immense, but it also provides many opportunities for generating new knowledge and its delivery.

Historically, applied manipulative studies of forests have tested the ability of specific silvicultural treatments to address regeneration and wood production objectives. Moreover, these traditional replicated forest experiments normally occupy scales of 0.5 to 5.0 hectares (UK FORESTRY COMMISSION, 2006). Examples of such studies are longterm growth and thinning trials providing data for yield tables (PRESSLER, 1865; SCHWAPPACH, 1890; SCHOBER, 1972) and more recently for density-dependent growth models (EK and MONSERUD, 1974; BURKHART, 1987; GADOW, 1987; SPELLMANN and NAGEL, 1992; PRETZSCH, 2001). Yet, current silvicultural questions are often focused at a wider array of issues that occur at broader landscape scales. Developing solutions to these questions requires an approach that links intensive study and operational trials. Both managers and researchers need to participate in the design of the work and the interpreting of the results and so gain from shared experience (UK FORESTRY RESEARCH COMMISSION, 2006). Changing societal values now demand these expanded approaches to forest management that also integrate social, ecological and economic goals. The role of silviculture in altering trajectories of stand structure and composition is vital to that success (e.g., see DEBELL and CURTIS, 1993; O'HARA et al., 1994). In their broad review of large multi-disciplinary studies, PETERSON and MONSERUD (2002) provided examples of manageable research questions that most experimental approaches strive to address:

• What do we need to know to determine the consequences of a change in the current mix of forest management values across the region?

• What are the relations of socioeconomic components to biophysical and management policies and practices as we move across different scales, from local (stand/watershed) to intermediate (province) to regional?

• What types of silviculture and conditions allow for the maintenance or improvement of the integrity of the riparian system while simultaneously managing for wood production?

Many recent (past decade) experimental manipulations have become multi-disciplinary in scope and approach and involve restorative treatments, novel silvicultural approaches or variants of more traditional approaches that are relevant to operational scales. Small-scale site based experiments play a useful role in the development of basic understanding but are unlikely to ascertain the full range of system responses at operational scales. As a result, the ecological science used as a basis for much of our management is largely composed of theories that are oftentimes untested (FRANKLIN, 1999a). The long-term nature of much of the relevant ecological science needed to develop operational management strategies such as system responses to disturbances and patterns occur over many decades or even centuries and over large landscape scales make validation particularly challenging (FRANKLIN, 2005).

Manipulative forest ecological experiments need to address a variety of responses to changes in forest structure or function. Some of the necessary data can be collected as a part of carefully designed monitoring programs but scientific experimentation also needs to be part of the validation process. Indeed, there are circumstances where monitoring can only be effectively accomplished by conducting a carefully designed experiment (FRANKLIN et al., 1999a). The silvicultural treatments employed in these experiments are increasingly designed by interdisciplinary teams with wood production, ecological, social or economic objectives as joint outcomes (FRANKLIN, 2005). Individually and collectively these studies represent major investments by research and land management organizations to meet increasing public demands for forests that provide healthy environments for people, sustain biodiversity, and ensure economic productivity.

Workshops held in 2003 (SZARO et al., 2004) and in 2004 (PETERSON and MAGUIRE, 2005) represent a new effort sponsored by IUFRO Divisions 1 and 4 that has focused on large-scale experiments for sustainable forestry. This paper summarizes the lessons learned from those workshops in designing, implementing and maintaining studies at operational scales.

3. LESSONS LEARNED

3.1 Suite of common issues/problems/challenges

Large-scale and long-term silvicultural experiments are needed to evaluate the effects of alternative forest management strategies on biological diversity, yet they are rarely undertaken due to the substantial commitments of time and resources required (AUBRY et al., 2004). Since large-scale management experiments are implemented at the scale at which management occurs these studies are typically longer term and include multiple objectives at multiple scales that cover a spectrum of natural resources topics (GANIO and PUETTMANN, 2005). As a result, designing studies that effectively incorporates these features can be challenging (GANIO and PUETTMANN, 2005). All long-term forestry research faces many of the same problems including continuity of financial support, longevity and persistence of researchers, data storage and access, the shifting of societal goals and values that were used in the original experimental design, etc (FRANKLIN, 2005; INNES, 2005). Long-term observations are essential elements in the science and application of resource management yet there are not likely to be very many of these experiments because of the difficulty and expense associated with establishing and maintaining long-term experiments in forest responses (FRANKLIN, 2005). Hence, such experiments need to focus on major paradigm shifts, such as fundamental changes in silvicultural practices. Another possibility is to work closely with resource managers in an adaptive management process to incorporate learning elements as part of many management activities.

Field experiments at the scale of management operations have several advantages but also some drawbacks (BRANG et al., 2003). Among the advantages are: 1) the potential to assess processes and factors which are relevant for system dynamics, but not completely understood at the beginning and 2) a better knowledge of stand development and often even initial conditions and some causal relationships, in comparison to purely retrospective approaches. The drawbacks include 1) problems with extrapolating the results to other sites (although not as great with small plot studies), 2) a considerable investment of resources, and 3) the necessity of a long-term commitment.

The DEMO (Demonstration of Ecosystem Management Options) experiment established in the Pacific Northwest during the last decade is an example of a study with its focus on structural retention as a part of regeneration harvest practices (a fundamental change in silvicultural practice). The development of the DEMO experiment exemplifies the difficulties of dealing with these issues (FRANKLIN et al., 1999b).

3.2 Common elements of design/approach

The objective of forest research is to reach a better understanding of biological and economic systems and to generate information that is useful for management. An important objective of forest management, on the other hand, is to utilize research information that is useful. These two objectives are not always easy to match in an increasingly fragmented scientific environment which rewards highly specialized investigation. Forests represent a remnant wilderness of high recreational value in the densely populated information societies, a natural resource threatened by elimination in impoverished regions and a renewable reservoir of essential raw materials for the wood processing industry. Thus, experimental design must account for both, specific local research objectives and interdisciplinarity.

One common element in many studies trying to develop new and innovative alternatives to traditional silvicultural practices particularly clear-cutting, focus on what is left behind, referred to as "retention" (FRANKLIN, 1997). Possible approaches range from variable-retention (AUBRY et al., 2004; BEESE et al., 2005; BUNNELL, 2005; HARRINGTON et al., 2005; D. MAGUIRE et al. 2005, SCHWARZ et al. 2005) alternative thinning regimes (BEGGS et al. 2005; MARSHALL and CURTIS, 2005), and even ways to provide connections between similarly managed areas (i.e. forest corridors or minimum distance between similar patches; see BAUGHMAN and GUYNN, 2005). Taken collectively, most of these experiments address one or more thinning treatments (uniform and/or irregular), variable-sized openings and patches (or "leave" islands) that when implemented, retaining some arrangement of forest structure (often either uneven-aged or two-aged systems) and range of aggregation or dispersal of individual trees that can be managed towards some future desired condition. The fact that all these experiments together comprise a diverse portfolio of approaches and designs with multi-disciplinary evaluations is one that should be valued in the forestry community (GADOW and KLEIN, 2005).

FRANKLIN (2004) gives some guiding principles in the development of large-scale and long-term forest experiments (*Table 1*).

Table 1

Developing and Designing Long-term Experiments (Modified from FRANKLIN, 2004).

Entwicklung und Design langfristiger Experimente (modifiziert nach FRANKLIN, 2004).

Keep them simple
Keep them statistically credible
Devote the necessary resources to data management
Build the capacity for sustaining the long-term studies
Provide leadership continuity

The statistical concerns and needs for replications, power analyses, appropriate experimental designs, and so forth for these newer kinds of approaches have received renewed interest (e.g., see BENNETT and ADAMS, 2004; GANIO and PUETTMANN, 2004; GADOW and KLEINN, 2005). In addition, the commitment of necessary resources, capacity and multi-disciplinary leadership (INNES, 2005) is a shared challenge globally.

3.3 Solutions at local/regional levels

Successful approaches to sustainable forest management are increasingly community-based and initiated by local people (JOHNSON et al., 1999; TORRES and MAGAÑA, 2006). Rapid cultural changes caused by the in-migration of numerous new people into traditional resource-based communities and surrounding areas may be underlying causes to changes in social values. There is a growing realization that a long-run approach to land use and management is generally better (ecologically and economically) for developing harmonious and sustainable relationships between people and the land (CAÑADAS, 2005).

3.4 Role of public acceptance/education

Successful approaches often include an educational element, which benefits both those who are actively engaged in ecologically-based assessment and decision-making processes, and others who may be affected by such processes (JOHNSON et al., 1999). A shared literacy and awareness about ecosystems, and about how humans rely on and affect them, can help to build receptivity and support for sustainably managing forests. This is especially important in the urban environment (GADOW, 2002). The educational process is often fostered by direct involvement in ecologically-based assessment and decision-making processes. The communication between managers, members of the public, scientists, and staff people involved in these processes leads to a broadening of their collective understanding of the ecosystems being addressed. It also increases the understanding of how human uses can act as vectors of change in ecosystems, and about ecosystem-compatible options for our use of them. The analysis and decision support models that are used in these processes facilitate learning about what variables are important, and what we know and don't know. Early and continuous involvement in these processes leads to a deepening understanding of sustainable forest management concepts and applications by all parties.

The educational process is also facilitated by the dissemination of ecological information between (and to) agencies, managers, scientists, and the public, especially when such information is communicated in language all parties can understand. It is also helped when the "lessons learned" through implementation are evaluated as to their transferability. However, the recent multi-disciplinary operational experiments in North America are incorporating more research components that use photos, visual simulations, and surveys to communicate and test public values for visual aesthetics of the new silvicultural treatments to be used by forest land managers (e.g., see BRADLEY, 2005; RIBE, 2005); these are primary (i.e., funded as part of the experiment) objectives in some studies (e.g., see AUBRY et al., 2004; REUTEBUCH et al., 2004).

3.5 Information to Knowledge

Long-term experiments are invaluable to forestry, but it is critical that the information that is generated by them is transformed into knowledge that can be used to improve forest management practices. There are many barriers to this, and most managers of long-term forest experiments are devoting so much time to the maintenance of funding for their work that there is little opportunity to address such issues as extension and uptake. This is creating a "vicious circle", as the funding is dependent on the managers being able to demonstrate the value of their experiments (INNES, 2005).

The conversion of information to knowledge and the dissemination of that knowledge to those who can best use it is a critical stage of any long-term forest research project. There is a need to better plan for this and to ensure that it becomes as an integral a part of project planning as the experimental design. Whether this can be achieved in the short-term remains to be seen (INNES, 2005).

Successful integration of training programs, networking, technology transfer, information dissemination and improved linkages among policy-makers, stakeholders and scientific communities are essential (SZARO, 2000). Developing reasonable solutions is very difficult in part because the method of knowledge generation and its delivery is in a period of uncertainty and flux because of several important drivers of change including democratization, market economics, globalization, technological innovation and the roles of public/private engagement. The fact of globalization and wide spread access to information means that the bulk of the knowledge to which access is needed will have been produced elsewhere. Over 90% of the knowledge produced globally is not produced where its use is required. The challenge is how take and find knowledge that may have been produced anywhere in the world and synthesize and deliver it so that it can be used effectively in particular problem-solving contexts for local and regional applications.

3.6 On the right trajectory

All of the experiments shared at both workshops showed that alternatives to clearcutting were operationally feasible and can enhance biodiversity conservation as well as providing some timber resources (VYSE et al., 2005). Some trials also showed that the alternatives can have some negative effects on at least some components of the forest ecosystem. As a consequence, widespread application of a single practice is unlikely to be sustainable but rather a suite of alternatives should be considered (MCCLELLAN, 2004; VYSE et al., 2005; MCCLELLAN and HENNON, 2005).

It is assumed that there are numerous ecological benefits of uneven-aged, continuous cover forest management, but validated research results are lacking and predictions are largely conjectural (GADOW, 2004). Although data are available on the ecological characteristics of unmanaged forests and clearcuts in the Douglas-fir region of North America, there is little quantitative information on how forest ecosystems will respond along a gradient of retention levels. Better information on the ecological effects and public responses to variable-retention harvesting systems is needed if forest managers are to achieve the objectives of continuous cover forest management (European terminology) or ecosystem management (North American terminology; see FRANKLIN et al., 1997).

3.7 Adaptive management

A managed forest ecosystem may be seen as an enterprise which produces a comprehensive set of goods and services and which constantly needs to adapt its production processes and its range of products in response to an evolving market. This objective can be achieved if research is made accessible at different levels, as is the case in most enterprises. Thus, it is often postulated that forest management should be sustainable, be based on validated research results, conform to acceptable environmental standards, and be transparent to the public. In an ideal world we would have enough information and be able to predict with sufficient certainty that we could just plan our management activities and be assured of the desired outcome (SZARO et al., 1999). Unfortunately, this is not the case because our understanding of ecosystems is not, and may never be, complete. There are inherent uncertainties within and among ecological, economic, and social systems. Surprises in the behavior of ecosystems are inevitable and management systems must be designed to adjust to the unexpected rather than act on the basis of a spurious belief in certainties (GADGIL, 1999; GUNDERSON, 1999). Therefore, an adaptive management approach (e.g., see WALTERS, 1986 and BORMAN et al., 1999) is essential for addressing uncertainty by structuring initiatives as experiments in which results are used to continually correct course (THE KEYSTONE NATIONAL POLICY DIALOGUE ON ECOSYSTEM MANAGEMENT, 1996). *Figure 1* illustrates the basic interactions that help define the research context: social values influence institutional policy, which in turn affects managerial decisions and actions, resulting in a mix of outcomes. Those decisions and proposed actions are evaluated – often challenged – by society prior to being implemented, as a normal part of the planning process (PETERSON and MONSERUD, 2002; SZARO and PETERSON, 2004).

A formal process of adaptive management can be used to maximize the benefits of any option for land and natural resource management and to achieve long-term objectives through implementation of ecosystem management (LESSARD, 1998). The process itself is straightforward and simple: new information is identified, evaluated, and a determination is made whether to adjust strategy or goals (SALAFSKY et al., 2001). It is a continuing process of action-based planning, monitoring, learning and adjusting with the objective of improving the implementation and achieving the desired goals and outcomes. In this process goals and objectives are clearly stated, an initial hypothesis of ecosystem behavior is described, and monitoring is conducted to provide feedback for redirection of management "experiments" or practices. While the concept of adaptive management is relatively straightforward, applying it to complex management strategies requires answers to several critical questions. What new information should compel an adjustment to the management strategy? What threshold should trigger this adjustment? Who decides when and how to make adjustments? What are the definitions and thresholds of acceptable results? Are thresholds even feasible to detect given the oftentimes latent effects

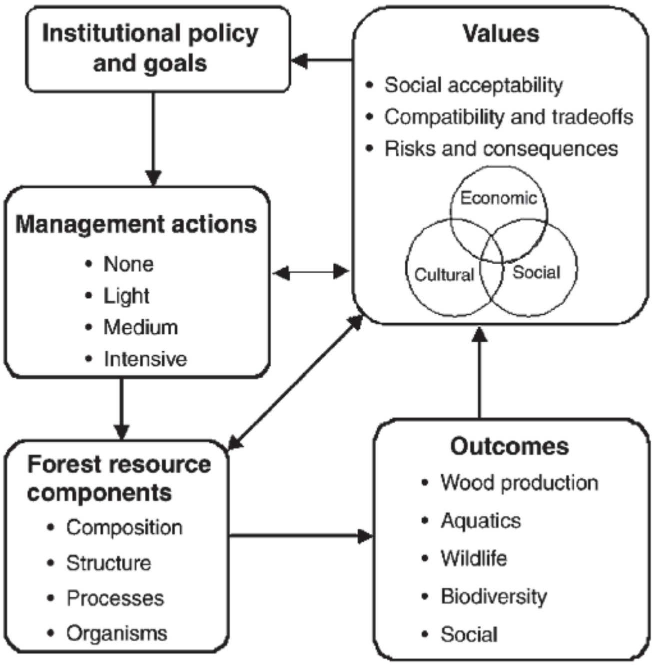

Fig. 1

Conceptual model showing interactions among forest resource components, societal values, institutions, management, and outcomes (From PETERSON and MONSERUD, 2002).

Modellvorstellung der Interaktionen zwischen Ressourcen, gesellschaftlichen Wertvorstellungen, Institutionen und Ergebnissen (nach PETERSON and MONSERUD, 2002).

of impacts? Adaptive ecosystem management depends on a continually evolving understanding of cause-and-effect relationships in both biological and social systems. Planning for and adapting to surprise will provide an actionary rather than a reactionary basis for more informed decisions.

This reiterative approach causes management execution and adaptation systems to make progress towards goals, even if the goals change with time (BASKERVILLE, 1985). It promotes an information-rich environment and a rationale for routinely monitoring and evaluating social, political, and biological environments. Feedback loops for an adaptive management process already partially exist within many societies. These can be in the form of project scoping activities, participation in project design, analysis, and review, special public forums, and in worst case scenarios – litigation and legislation (EVERETT et al., 1993).

4. SUMMARY

The general public is getting more acquainted with forestry and demands a high level of sophistication of forest management (GADOW, 2004). Greater research involvement is called for and the ultimate objective of field experiments, which often represent major investments, is to meet increasing public demands for forests that provide a healthy environment for urban people, a biologically diverse and near-natural habitat and sustainable yields of forest products. There is no obvious right or wrong way to integrate science into the decision-making process but the differences between the development of scientific knowledge and its consideration need to be recognized. In science, the following of a relatively formal process is the norm leading to the acceptance of that information within the scientific community. However, the acceptance of scientific results by policy-makers, decision-makers and the public may differ markedly and be heavily influenced by personal perceptions and values.

The last two decades have witnessed a dramatic shift in perspective on how forest land should be managed (SZARO and PETERSON, 2004). In response, forest research and development has added new integrative and large-scale experiments that can better evaluate joint outcomes and improve policy and management decision-making. These large-scale experiments help in adapting management actions to achieve desired outcomes by providing alternatives that integrate across sectors in real-time scenarios.

Given the uncertainties involved in making long-term management decisions in the face of incomplete knowledge, these large-scale experiments are a step in the direction of true adaptive management strategies. Adaptive management is an approach that needs to be considered more broadly to ensure that desired outcomes can be achieved over time. Careful monitoring of outcomes both advances scientific understanding and helps adjust policies or operations as part of an iterative learning process. It is this link between iterative learning and associated iterative improvements to management that is the key to a sustainable future.

5. Zusammenfassung

Titel des Beitrages: *Großflächige Feldversuche für die nachhaltige Waldnutzung.*

Die klassischen forstlichen Feldversuche wurden angelegt, um die Auswirkungen bestimmter forstlicher Nutzungseingriffe auf das Baumwachstum und die Holzerträge zu untersuchen. Die gesellschaftlichen Ansprüche an die Waldnutzung haben sich mit der Zeit geändert; sie haben eine Erweiterung erfahren und umfassen heute soziale, ökologische und ökonomische Zielsetzungen. Infolge dieser Entwicklung sind Feldversuche heute in der Regel multi-disziplinär und oft auch großflächig konzipiert. Zahlreiche Wissenschaftler mit unterschiedlichen Erfahrungen beteiligen sich an der experimentellen Manipulation und Datenerfassung in Freilandstudien. Das Ziel ist die Untersuchung neuartiger Waldbauverfahren, oder Varianten herkömmlicher Verfahren, unter möglichst operationalen Bedingungen, d.h. auf Flächen, die die Größe der traditionellen Versuchsanlagen zum Teil weit übertreffen. Wir untersuchen in diesem Beitrag unterschiedliche waldökologische Feldstudien mit einer Vielzahl möglicher Reaktionen auf experimentelle Manipulationen, die eine Veränderung der Waldstruktur und -funktion bewirken. Die experimentellen Managementsysteme in den großflächigen Feldstudien werden in der Regel durch interdisziplinäre Teams konzipiert, unter Beteiligung der Natur-, Sozial- und Ingenieurwissenschaften. Die Auswertungen beziehen sich nicht nur auf Aspekte der Holzproduktion, sondern auch auf waldökologische und sozialökonomische Perspektiven der Waldnutzung. Im Einzelfall und in der Gesamtheit handelt es sich bei diesen Feldstudien um größere Investitionen von Forschungsorganisationen und anderen Geldgebern, die das Ziel verfolgen, nicht nur die Nutzfunktionen der Wälder, sondern auch der zunehmenden Nachfrage nach deren Schutzfunktionen und nach dem Erhalt der biologischen Diversität Genüge zu tun. In einem ersten IUFRO workshop in Davos/Schweiz (SZARO et al., 2004) und einer darauffolgenden zweiten Konferenz in Portland/Oregon (PETERSON and MAGUIRE, 2005) wurden vor allem Erfahrungen im Zusammenhang mit großflächigen Feldversuchen ausgetauscht. Dieser Beitrag fasst die wichtigsten Ergebnisse der beiden Veranstaltungen zusammen.

6. Résumé

Titre de l'article: *Etudes en plein champ et sur des surfaces importantes en vue de l'exploitation durable des forêts.*

Les recherches forestières classiques au champs ont été installées pour détermine quelles étaient les conséquences de telle ou telle méthode d'exploitation forestière sur la croissance des arbres et la production ligneuse. Au cours du temps les exigences sociétales concernant l'utilisation des forêts se sont modifiées; elles se sont élargies et englobent aujourd'hui des objectifs sociétaux, écologiques et économiques. Par suite de cette évolution les expériences sur le terrain sont maintenant en règle générale multidisciplinaires et portent souvent aussi sur des surfaces importantes. De nombreux scientifiques – aux habitudes différentes – participent aux traitements expérimentaux et à la collecte de données dans des études sur le terrain. L'objectif est la recherche de nouvelles méthodes de sylvicultures ou de variantes aux procédés habituels dans des conditions opérationnelles autant que faire se peut, c'est à dire que ces essais portent en partie sur des surfaces qui dépassent largement celles des dispositifs expérimentaux traditionnels. Dans cet article nous étudions les différentes expériences au champ d'écologie forestière ayant un grand nombre de réactions possibles aux manipulations expérimentales qui entraînent des modifications de la structure et du rôle de la forêt. Le système du management expérimental dans ces études au champ sur des grandes surfaces est en principe conçu par une équipe interdisciplinaire qui fait appel aux sciences de la nature, sociales et à celles de l'ingénieur. L'exploitation des résultats ne se limité pas au seul aspect production ligneuse mais concerne également les conséquences écologiques et sociétales de la récolte de bois. En particulier comme en générale il s'agit avec ces études sur le terrain d'obtenir des investissements assez importants des organismes de recherches et d'autres bailleurs de fonds en vue d'objectifs qui ne concernent pas que la fonction de production de la forêt mais également les exigences croissantes concernant son rôle de protection et celui qu'elle joue pour le maintien de la diversité biologique. Lors d'une première intervention à l'IUFRO à Davos/Suisse (SZARO et col., 2004) puis lors d'une deuxième conférence qui a suive Portland/Oregon (PETERSON et MAGUIRE, 2005) furent surtout exposées

les expériences en liaison avec les recherches sur le terrain intéressant de grandes surfaces. La présente contribution résume les résultats les plus importants obtenus par ces deux organismes. J. M.

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Large-scale, long-term silvicultural experiments in the United States: historical overview and contemporary examples

(With 6 Tables)

By R. S. Seymour[1], J. Guldin[2], D. Marshall[3] and B. Palik[4]

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KEY WORDS – SCHLAGWORTER

Experimental forests; multi-aged silviculture; regeneration methods; clearcutting; biodiversity; experimental design; structural retention; gap harvests.

Versuchswald; ungleichaltrig; Dauerwaldmanagement; Verjüngungsverfahren; Kahlschlag; Biodiversität; Versuchsflächendesign; „structural retention“; Lochhiebe.

1. INTRODUCTION

This paper provides a synopsis of large-scale, long-term silviculture experiments in the United States. *Large-scale* in a silvicultural context means that experimental treatment units encompass entire stands (5–30 ha); long-term means that results are intended to be monitored over many cutting cycles or an entire rotation, typically for many decades. Such studies were installed widely between 1930 and 1955 when forest rehabilitation accomplished by partial cutting dominated research and practice, but fell from favor during the profound nationwide switch to even-aged silviculture during the 1960s (Seymour, 2004). Concerns over the widespread use of clearcutting and the resulting even-aged regimes have rekindled an interest in the use of other silvicultural systems and large-scale and long-term experiments. Contemporary studies (since 1990) from four representative forest regions of the United States – the Northeast, Lake States, mid-South, and Pacific Northwest – are described and compared. Notable contributions of early (ca. 1925–1950) experiments, some of which remain active, are also reviewed, and contrasted to modern studies.

2. HISTORY

2.1 The Era of "Selective Cutting": 1925–1960

Silvicultural research in the United States received a major stimulus in the late 1920s with the report from a National Academy of Sciences panel (Bailey and Spoehr, 1929) and related passage of

[1]) University of Maine, Orono, ME 04469, USA.
E-Mail: Seymour@umenfa.maine.edu

[2]) USFS Southern Research Station, Monticello, AR 71656, USA.

[3]) USFS Pacific Northwest Research Station, Olympia, WA 98512, USA.

[4]) USFS, North Central Research Station, Grand Rapids, MN 55744, USA.

the McNary-McSweeney by Congress in 1928. By contrasting agricultural experimentation with silviculture experimentation, Bailey and Spoehr discounted the future of intensive production forestry that would later gain prominence during the 1960s, and instead, forecast that „... silviculture will be concerned, at least for an extended period, with the modification of relatively natural units of vegetation and with the restoration of more or less natural arborescent growth on devastated areas, rather than as in agriculture with extending the culture of a limited number of highly domesticated species under comparatively artificial conditions (p. 6).“ They noted that the advance of forestry in Europe and Japan had been founded on „an efficiently systematized empiricism,“ and concluded that “... the extension of silvicultural management over the earth's vast area of wild forest land must be preceded by a comprehensive descriptive survey and analysis..., and by an intelligently formulated program of empirical experimentation...” (BAILEY and SPOEHR, 1929, p. 16).

In response to these developments, the US Forest Service established experimental forests with large-scale trials of contrasting harvesting methods, nearly all of which were various forms of partial cutting using natural regeneration. Early examples set up prior to World War II, such as the Dukes Experimental Forest (ca. late 1920s) in the old-growth northern hardwoods of Michigan's Upper Peninsula (EYRE and ZILLGITT, 1953) and the Crossett Experimental Forest (ca. 1934) in the loblolly-shortleaf pine forests of the Gulf Coastal Plain (BAKER and BISHOP, 1986) were typically unreplicated. A prominent objective of these early empirical studies was demonstrating what the researchers of the time considered to be “good forestry”: typically light, frequent cuttings that built up and maintained high levels of growing stock (REYNOLDS, 1959; REYNOLDS, 1969). During the late 1940s, the Society of American Foresters' Division of Silviculture formed a “subcommittee on large-scale silvicultural tests” which compiled a detailed protocol for what had become known as “compartment studies” (OSTROM and HEIBERG, 1954). They recommended that treatments include various silvicultural systems of stand management and regeneration, product objectives or rotation length, intensity of cultural treatment, and volume of residual growing stock.

They focused exclusively on production and regeneration; non-commodity values were not mentioned. Also, the value of untreated controls, an essential feature in modern studies, was also not discussed, presumably because the “no-management” scenario was not viewed as a realistic option during this era. By the 1940s, some of Fisher's principles of experimental design were being addressed, and entire experimental forests were dedicated to replicated trials of alternative silvicultural systems. For example, the Penobscot Experimental Forest (ca. 1950) in the mixed northern conifer forests of east-central Maine contains two replicates of eight contrasting silvicultural systems (but no replicated controls), encompassing over 160 ha (SENDAK et al., 2003). Similarly, the Argonne Experimental Forest cutting methods study (ca. 1951) in second-growth northern hardwoods in Wisconsin contains three replicates of six treatments, including an untreated control (STRONG and ERDMANN, 1995). The Crrossett Experimental Forest installed a replicated study that compared growth and yield over time among two even-aged and two uneven-aged silvicultural systems, but without unmanaged controls (CAIN and SHELTON, 2001).

Although results often took two or more decades to develop, these early studies have made countless contributions to the management of natural forests in the United States. They provided the first reliable yield data for managed stands (e.g., EYRE and ZILLGITT, 1953; SOLOMON and FRANK, 1978; REYNOLDS, 1969; BAKER and MURPHY, 1982; GULDIN and BAKER, 1988); prior to ca. 1950, foresters were limited to normal yield tables that were applicable only to fully stocked, even-aged stands. Further observations on these studies after three or four decades provide further information on the sustainability of selection stand structures (e.g., FRANK and BLUM, 1978; SEYMOUR and KENEFIC, 1998; BAKER, 1986; BAKER et al., 1996; CAIN and SHELTON, 2001); indeed, the empirical northern hardwood structure derived by ARBOGAST (1957) from the EYRE and ZILLGITT (1953) studies has become virtually institutionalized in the Lake States and is widely used throughout the US range of *Acer saccharum* (SEYMOUR, 1995). Recent publications have documented the deleterious ecological effects of diameter-limit cutting, an exploitative harvest practice included in some early studies that remains common in mixed-species forests of eastern North America (KENEFIC et al., 2005).

2.2 The Era of Production Forestry: 1960–1990s

About 1960, many American foresters realized that “selective cutting” as generally practiced (with inattention to stand structure and regeneration) had not lived up to the potential of the selection system as envisioned by its early advocates (SEYMOUR, 2004). An abrupt paradigm shift to even-aged silviculture focusing on high-yield and low-cost wood production took effect in nearly every forest and ownership type in North America (BOYCE and OLIVER, 1999). Rapid progress in forest biology and quantitative sciences supported a widespread acceptance of a high-yield agricultural paradigm for forestry. Research emphasis shifted away from natural regeneration and growing stock levels to high-yield practices such as site preparation, planting, early vegetation management, and thinning. Many of these studies were (or are) long-term in nature (e.g., CURTIS and MARSHALL, 1997; WAGNER et al., 2004), but owing to uniform stand structures and monoculture compositions, large, stand-scale compartments were no longer necessary for study. Plot sizes of 0.1 ha or less, two orders of magnitude smaller than the 10-ha units in the old compartment studies, allowed field studies to examine numerous treatments without sacrificing adequate replication. Research administrators and many scientists came to regard compartment studies as costly, low-power experiments on the wrong topics, diverting resources away from high-yield studies. Compartment studies soon fell into disfavor, and many studies were either closed or neglected for decades.

The force of this paradigm shift led the profession away from a broad view of silviculture. Research emphasized various elements of plantation forestry, to considerable effect. Arguably, the two most influential advances in American silviculture during the last half of the 20th century were the advances in genetically improved planting stock and the development of herbicides that act very specifically in small doses to interfere with physiology and biochemistry of woody plants. These effective agronomic technologies became so closely associated with clearcutting that silvicultural systems using other regeneration methods were neglected and often derided. As a consequence, experimentation with silvicultural systems other than those associated with intensive forestry was so infrequent that scientists who did engaged in it were regarded as iconoclasts. Advances in such alterative systems from this period were typically limited to new analyses of the older studies, as well as reports on unreplicated demonstrations over a longer term than is typically observed (e.g., MURPHY, 1983; BAKER, 1986).

2.3 The Era of Ecological Forestry: 1990–Present

By the late 1980s, growing reservations about the effect of widespread application of the even-aged production forestry model on natural ecosystems and controversy over harvest of old-growth prompted another shift in silvicultural paradigms focused on US National Forests. Much of this drama was played out in numerous court battles. In the Pacific Northwest, harvesting was effectively stopped on federal lands and a presidential summit was convened to resolve the conflicts in managing national forests. The result was the development of the Northwest Forest Plan (TUCHMANN et al., 1996). Many of the ideas used in developing this plan and influencing new management directions across the United States were stimulated by Franklin's (1989) plea for a "new" forestry and Hunter's (1990) influential book that introduced biodiversity to a skeptical profession in a non-threatening package. On public forests, a more naturally focused silviculture was again in vogue, and diversity in stand structure and composition became important management objectives.

Although it may be tempting to describe this as the pendulum swinging back to the 1930s, this new era of ecological forestry (*sensu* SEYMOUR and HUNTER, 1999) is quite different in several respects. As the earlier quote from BAILEY and SPOEHR suggests, scientists of the 1920s favored natural regeneration and conservative treatment of the growing stock because of its inherent economy in meeting production targets; they could not anticipate the prosperity of the 1960s and the willingness of private landowners to invest in costly agronomic practices simply to grow trees. In contrast, the contemporary incarnation of natural-stand forestry is founded heavily on disturbance ecology, under the belief that operating within nature's limits (the historical range of variability concept) is a conservative way to manage for biodiversity (the coarse-filter concept) (SEYMOUR and HUNTER, 1992; FRANKLIN et al., 1997). A prominent element is the restoration of ecological processes, such as prescribed burning or partial disturbance events emulated by silvicultural practices in systems other than clearcutting. Socio-political issues were also quite influential; regardless of how "natural" stand-replacing disturbances might be in a given forest's historical disturbance regime, their ecological mimicry via large-scale clearcutting was simply unacceptable to a growing number of public stakeholders.

Perennially important issues such as stand production, growing stock levels, and investments in cultural treatments are not commonly mentioned, or are discussed in association with other commodity and non-commodity forest derived benefits. The fact that revenues from timber production can sponsor practical implementation of systems developed as alternatives to clearcutting, especially those based on ecological restoration (GULDIN et al., 2004), is less commonly discussed.

3. CONTEMPORARY LARGE-SCALE SILVICULTURAL EXPERIMENTS

Beginning in the early 1990s, the emergence of ecological forestry and urgency for alternatives to clearcutting on public forests began to spawn new large-scale experiments designed to address a comprehensive suite of silvicultural systems rather than just treatments. This need was particularly acute in the Pacific Northwest, which had no such existing experiments to resurrect (MONSERUD, 2002). Although partial cutting was practiced there during the 1930s as in other regions, and the method received a certain early acclaim (KIRKLAND and BRANDSTROM, 1936), experimental assessment was limited to unreplicated post-harvest monitoring plots that were abandoned after only a decade (CURTIS, 1998).

To illustrate the features of these new experiments, we review and contrast one example from four regions in the United States:

1. The Acadian Forest Ecosystem Research Program (AFERP): mixed northern conifer forest of east-central Maine; established 1994 and administered by the University of Maine; located on the Penobscot Experimental Forest (SAUNDERS and WAGNER, 2005; SEYMOUR, 2005).
2. Restoring Complex Structure and Composition in Great Lakes Pine Ecosystems (RSCP): second-growth red pine forests in Minnesota; established 2001 and administered by the USDA Forest Service, North Central Research Station; located on the Chippewa National Forest (PALIK and ZASADA, 2003; PALIK et al., 2005).
3. Ouachita Mountains Ecosystem Management Research Project (OMEM): shortleaf pine-hardwood forests in Arkansas; established 1992 and administered by the USDA Forest Service, Southern Research Station; located on the Ouachita and Ozark-St Francis National Forests (GULDIN, 2004).
4. Silvicultural Options for Young-growth Douglas-fir Forests (SOYDF): second-growth coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco); established 1998, administered jointly by the Pacific Northwest Research Station and Washington State Department of Natural Resources; located originally on the Capitol State Forest in Washington (CURTIS et al., 2004) and recently replicated on Vancouver Island (British Columbia, Canada) as part of the Silviculture Treatments for Ecosystem Management in the Sayward (STEMS) study (DE MONTIGNY, 2004).

3.1 Objectives

Although each study has many detailed objectives, two overarching goals seem to drive these studies. The null hypothesis of the SOYDF and OMEM studies, both of which include a full suite of common American silvicultural systems, is that regeneration success of the favored shade-intolerant species [Douglas-fir, shortleaf pine (*Pinus echinata* Mill.) under various systems of partial overstory retention does not differ from that of clearcutting. This reflects silviculture's first principle of sustainability: no regeneration method can be considered successful if it cannot reproduce the dominant or desired overstory species. In contrast, the AFERP and RSCP studies address the issue of active ecological restoration, in which all treatments are hypothesized to accelerate restoration of structural and compositional diversity in forest types simplified from past human activity (PALIK and ZASADA, 2003; FRIEDMAN and REICH, 2005).

3.2 Experimental Design and Treatments

All studies use the time-tested randomized complete block design with all treatments represented at a single location (*Table 1*). Treatment units are large (10–30 ha) and were randomly assigned within each block. The SOYDF and OMEM studies envision inference at the regional scale, with replicates installed throughout the forest type in question. The RSCP and AFERP studies are more narrowly focused geographically, with replicates only in a single forest. Replication is necessarily minimal (3–4), limited by the cost of installing and monitoring the large area in each experiment (90–780 ha).

All studies include commonly suggested alternatives to clearcutting and employed overstory retention during harvest: specifically, structures with uniformly dispersed overwood trees are compared against spatially aggregated patterns involving regeneration in gaps of various sizes (*Table 2*). Retention of mature trees and other biological legacies at harvest (FRANKLIN et al., 1997; MITCHELL et al., 2004) has been widely advocated in North America as a key approach for sustaining or restoring structural complexity (e.g., WATANABE and SASAKI, 1994; LARSEN, 1995; SULLIVAN et al., 2001; VANHA-MAJAMAA and JALONEN, 2001; MITCHELL and BEESE, 2002; BEESE et al., 2003; PALIK et al., 2002; AUBRY et al., 2004; BEBBER et al., 2004; BRAVO and DIAZ-BALTEIRO, 2004; HALPERN et al., 2005). Retention management approaches reflect the fact that natural post-disturbance stands often display more complex structure than is typical after traditional clearcuts (LINDENMAYER and FRANKLIN, 2002), with a spatially heterogeneous landscape that includes living trees, dead wood, and undisturbed patches of understory. This diversity provides the context for regeneration and continuity of ecological functions in the developing stand (FRANKLIN and MACMAHON, 2000; FRANKLIN et al., 2000).

The SOYDF and OMEM studies include delayed regeneration treatments (thinnings) as well as conventional clearcuts, thereby

Table 1
General Study Design.
Merkmale der Versuchsanlagen.

Study	Forest Type	Year(s) Established	Experimental Design	Treatments (incl. control)	Blocks (replications)	Size of. Treatment Unit (ha)	Total Area in Experiment (ha)
Silvicultural Options for Young-growth Douglas-fir (SOYDF)	Coastal *Pseudotsuga menziesii*	1998-2004	Randomized Block	6	3	13-29	300
Ouachita Mountains Ecosystem Management Research Project (OMEM)	*Pinus echinata* - hardwoods	1992	Randomized Block	13	4	15	780
Restoring Complex Structure and Composition in Great Lakes Red Pine Ecosystems (RSCP)	Lake States *Pinus spp.*	2001	Randomized Block	4	4	16	259
Acadian Forest Ecosystem Research Program (AFERP)	Mixed northern conifers-hardwoods	1995-97	Randomized Block	3	3	10	90

Table 2
Treatments Included.
Behandlungsvarianten.

Study	Clearcut	Untreated Control	Dispersed Retention	Gaps or Patches	Single-tree Selection	Thinning (Delayed Regeneration)
SOYDF	Yes	Yes	Yes	Yes (2 sizes)	No	Yes
OMEM	Yes	Yes	(2) Uniform shelterwood, Seed tree	Yes	Yes	Yes
RSCP	No	Yes	Yes	Yes (2 sizes)	No	No
AFERP	No	Yes	PEF[1]	Yes (2 sizes)	PEF[1]	PEF[1]

[1] Treatment replicated twice in nearby compartment study on the Penobscot Experimental Forest.

providing a full suite of common North American silvicultural systems. Because clearcutting has been the proven regeneration method for these species, the inclusion of this treatment represents another form of "control" against which to benchmark regeneration success under alternative treatments. Clearcutting was considered for inclusion into the RSCP study, but was dropped because the interest of the Chippewa National Forest was specifically to evaluate alternatives to this method, as well as the fact that regeneration response of the target species (*Pinus resinosa*, *P. strobus*, *P. banksiana*) to clearcutting has been thoroughly studied (BLAKE and YEATMAN, 1989; WEBER et al., 1995; PITT et al., 2000). AFERP does not include a clearcut treatment because this regeneration method is not recommended for most species of the Acadian forest (SEYMOUR, 1995).

Unlike the compartment studies during the selective cutting era, all modern experiments include randomly assigned untreated controls. Historical reconstructions at each site reveal that these untreated units are themselves former clearcuts; as such, they represent early- to mid-successional vegetation structures, and presently do not include all of the structural elements of late-successional old-growth in their respective forest types. In the short term, unmanaged units represent closed-canopy conditions that are valuable for a myriad of experimental purposes; in the long-run, they are intended to provide examples of natural successional pathways, and thus serve as benchmarks against which active silvicultural interventions can be compared ecologically. The latter role is especially critical in the RSCP and AFERP experiments where treatments have a strong restoration theme and are explicitly designed to accelerate development of late-successional, ecologically complex conditions.

All modern experiments also include treatments in which regeneration is concentrated in small gaps or patches that occupy 10–40% of the unit (*Table 3*). In the RSCP study the matrix was also underplanted experimentally to evaluate seedling response to a range of densities. Because historical silvicultural systems and experiments in the United States have tended to stress uniform stand treatments, gap cuttings are perhaps the most original and innovative ones in these modern experiments. Three studies explicitly vary gap size in two contrasting treatments; the OMEM study includes a range of gap sizes within its group selection treatment. In all but one case, the matrix between gaps was also treated at the time of gap creation by various prescriptions shown in *Table 3*; all would be considered fairly standard ways to treat stands uniformly if the gaps were not a part of the prescription. In addition, the matrix in the SOYDF study will be reduced on a 10-year cutting cycle. Finally, note that gaps were planted in two studies; the other two rely on natural regeneration.

The within-stand patchiness induced by gap harvests complicates monitoring in ways not apparent with uniform treatments. The problem stems from the systematic grids which are used to locate permanent monitoring plots prior to any treatment marking. We assume such a sampling pattern is unbiased with respect to the original uniform overstory; however, gaps or patches may also be located quasi-systematically in order to distribute them throughout the stand. Moreover, in practice, gaps are often located based on silvicultural objectives such as releasing accidentally established advance growth, restoring locally understocked conditions, or harvesting groups of surplus trees relative to structural targets. In addition to these possible sources of bias, the sampling intensity is designed to give adequate precision on overstory phenomena over the entire area, and is thus inadequate for the small fraction of the stand in gaps. One solution lies in measuring gap areas, creating two distinct strata, and computing weighted treatment means to quantify the overall stand response. However, this does not adequately capture the response of seedlings to well-known ecological gradients within gaps (distance from edge relative to stand height, position within the gap); such information requires a sampling system that explicitly addresses these factors.

All studies include retention of reserve trees in dispersed patterns (*Table 4*); typically between 10–20% of the pre-harvest stand basal area is reserved either permanently (AFERP, OMEM) or harvested after one 60-year rotation (SOYDF). The RSCP study retains a much higher density of reserves (basal area = 16 $m^2\ ha^{-1}$), the fate of which will be decided after 60 years with no cutting. The OMEM study retains 4.6 $m^2\ ha^{-1}$ of reserve-tree basal area in both the shelterwood and seed-tree treatments; seed trees are simply left standing after a 10-year regeneration period, at which point shelterwood overwoods are reduced to a final seed-tree density. The AFERP experiment retains reserve trees **within gaps**; about 4 $m^2\ ha^{-1}$ (10%) is designated for retention as the gaps are created and expanded. Some gaps in the OMEM also retained 2–3 m^2 of residual hardwoods for mast production.

Biodiversity is monitored to varying degrees in all studies, although no study consistently has had the resources to track a comprehensive suite of organisms routinely (*Table 5*). Such multidisciplinary studies are costly (*Table 6*), and often require expertise beyond that of the administering agency. Studies that monitor animal taxa appear to have higher annual monitoring costs than those

Table 3
Details of Gap/Patch Treatments.
Details der Lochvarianten.

Study	Gap Sizes (ha)	Area in Gaps (%) per Entry	Cutting Cycle (years)	Gap Regeneration. Method	Matrix Treated?
SOYDF	.04 - 0.6 0.6 - 2.0	20%	15	Planted	Thinned to 45% relative density
OMEM	0.2 - 0.8	17%	10	Natural	Target reverse-J dbh structure
RSCP	0.1 0.3	30-40%	60	Planted (3 Pinus spp.)	Thinned from below, such that entire area averaged 16m^2/ha basal area (incl. gaps)
AFERP	0.1 0.2	10% 20%	10	Natural	One-time improvement cutting in 20% treatment only. None in 10% treatment.

Table 4

Details of Dispersed Retention Treatments.

Details der verteilten Retentionsvarianten.

Study	"Label"	Level of Retention (Basal Area)	Long-term fate of reserve trees
SOYDF	Two-aged	20% (=37 trees/ha)	One rotation of young cohort
OMEM	Seed-tree	4.6 m^2/ha	Seed trees retained permanently
	Shelterwood	9.2 m^2/ha	Shelterwood overwood reduced by 50% after 10 years, then retained permanently
RSCP	Dispersed Retention	16 m^2/ha	One rotation of young cohort (60 years)
AFERP	Irregular Group Shelterwood with Reserves *(Femelschlag)*	10% (= 4 m^2/ha)	Selected when overwood is removed from regenerating 0.2 ha groups; retained permanently.

Table 5

Elements of Biodiversity Monitored.

Elemente des Biodiversitäts-Monitoring.

Study	Herbac. Veg.	Coarse Woody	Birds	Amphib.	Invert.	Other
SOYDF	Routine	Blowdown events only	Ad-hoc	No	No	
OMEM	*Ad-hoc*	*Ad-hoc*	Routine	Routine	*Ad-hoc*	
RSCP	Routine	Routine	Routine	*Ad-hoc*	*Ad-hoc*	Routine: Various insects and pathogens
AFERP	Routine	Routine	*Ad-hoc*	*Ad-hoc*	*Ad-hoc*	

limited to plants, although the sheer size of the experiment is obviously also a major determinant.

3.3 Replication and Statistical Power

Although large-scale studies are very expensive, our experience suggests that stand-scale treatment units are essential for studying any silvicultural treatment that purposely creates within-stand diversity, whether it be single-tree selection to a diameter structure or a gap-based system. Consider a gap treatment that creates 0.4 ha openings over 20% of the stand in each of a series of five entries. Such a system "repeats" every 2 ha within the stand, so stands must be 10–20 ha in order to have multiple repetitions of the pattern. Replicates of only 2-ha in this case would be overwhelmed with "edge effects" as they abutted other treatments, analogous to installing a 20% thinning treatment by removing one tree on a five-tree plot. Furthermore, stand-scale units help ensure that treatment technologies will be feasible and costs will be realistic if such systems are embraced operationally. Finally, treatment units must be large enough to encompass the home ranges or territories of keystone animal species that serve as important indicators of biodiver-

Table 6
Study Costs.
Kosten der Versuchsanlage.

Study	Establishment (includes planting, veg. management)	Annual Measurements and Maintenance
SOYDF	$ 312,000	$7,500
OMEM	$ 1,000,000	$ 300,000
RSCP	$1,000,000	$120,000
AFERP	$120,000	$30,000

sity. If it were not for this last issue, one could argue that clearcut and uniform dispersed retention treatments could be represented in much smaller units.

Although such large treatment units obviously work against adequate replication, the need to study silvicultural systems and ecological phenomena at appropriate scales leaves silviculture scientists no choice. Although testing null hypotheses at an arbitrary probability of 0.05 often seems inviolate in such experiments that follow the classic randomized block model, this issue may be worth revisiting in cases where replication is so expensive. For example, it is interesting to consider the consequences of a Type II error – failing to reject the null hypothesis owing to low power from insufficient replication and perhaps high variability. In the SOYDF and OMEM studies, such an error might take the form of a finding whereby some parameter of regeneration success under certain overstory retention or gap treatments is not different statistically from the proven method of clearcutting. Users predisposed to abandoning clearcutting would immediately embrace alternatives with a false confidence, only later to find that the alternatives experienced regeneration problems. In the AFERP and RSCP studies, a Type II error might conclude that certain gap treatments had no negative effect on songbird nesting relative to the untreated control; managers would then proceed with gap harvests that may have negative effects. Now, imagine if the test had been done at p = .33 instead of .05 and **had** suggested differences; what would managers do in these cases? It is at least possible that they would respond differently, thus illustrating the importance of choosing rejection probabilities that are realistic given the context of the expected effect size and costs of alternative actions.

3.4 Strengths of Large-scale Studies

Beyond the necessity of treating entire stands and monitoring at ecologically appropriate scales, large-scale studies have other benefits. When scientists work at the same scale as managers, researchers gain appreciation for operational realities such as limitations of harvesting systems and costs of planting and tending treatments. The joint ownership resulting from partnerships between scientists and managers has immeasurable value in bringing credibility and relevance to the research (MARSHALL and CURTIS, 2005). Study sites provide "life-sized" examples of innovative silvicultural systems, which help convince managers of their operational feasibility and provide a training ground. Finally, installations offer great field laboratories for non-silviculturists to study ecological phenomena in the context of well documented and professionally executed silvicultural systems. Examples include small-scale studies of gap regeneration, salamander dispersal, wood decomposition, tree ecophysiology, whole-stand studies of avian population ecology, nutrient cycling, remote sensing, and public perceptions.

4. CONCLUSIONS

Long-term, large-scale silvicultural experiments, both old and new, are critical chapters in American forestry. Since the 1920s, treatments included in these experiments constitute the best attempts of the nation's top research silviculturists to address the pressing problems of each region and time period. Without them, the profession would lack the essential scientific framework that is central to forest sustainability at all levels. Finally, silvicultural research, like any other applied discipline, has no value unless it is **used**. Although sound science is essential, our experience suggests that convincing skeptical managers to embrace novel ideas and practices is as much a marketing challenge as it is a scientific one. Without these operationally oriented laboratories of managed forest vegetation designed to illustrate the choices available to managers, we would have little to offer beyond anecdotes and opinions extrapolated from small-scale narrowly focused studies.

5. ABSTRACT

This paper reviews experience and research findings from selected large-scale, long-term silvicultural experiments in four regions of the United States: the Northeast, the Lake States, the mid-South, and the Pacific Northwest. As early as the 1920s, when there was nationwide interest in multi-aged silviculture, researchers recognized that silvicultural systems involving within-stand variation in age and size structure could not be tested effectively on small (<1 ha) plots, and began installation of compartment-scale (10–20 ha) trials on many experimental forests throughout the United States. Large-scale trials have experienced a revival in the past decade for several reasons: a search for alternatives to clearcutting that successfully regenerate shade-intolerant species; a renewed interest in managing for within-stand structural complexity, and a need to test hypotheses about biodiversity that occur at the scale of entire forest stands. Large-scale experiments are difficult and expensive to install, properly replicate, monitor, and maintain over time, but also have many benefits: (1) scientists learn to appreciate operational realities of forest managers, such as limitations of harvesting systems; (2) study sites provide "life-size", realistic examples of innovative silvicultural systems, and thus are more readily understood and embraced by practitioners; and (3) installations offer great field laboratories to study a wide range of questions from small-scale phenomena, such as amphibian dispersal and seedling development, to whole-stand responses in the context of a well-documented and professionally executed silvicultural systems.

6. Zusammenfassung

Titel des Beitrages: *Großflächige, langfristig angelegte waldbauliche Feldexperimente in den USA, historische Übersicht und gegenwärtige Beispiele.*

Dieser Beitrag berichtet über Erfahrungen und Forschungsergebnisse ausgewählter langfristiger waldbaulicher Feldversuche in vier Regionen der Vereinigten Staaten von Nordamerika: im Nordosten, im Gebiet der Großen Seen, im Mittleren Süden und im Pazifischen Nordwesten. Bereits in den 20er Jahren des letzten Jahrhun-

derts, als man sich überall in den USA für Dauerwaldsysteme interessierte, erkannten Forscher, dass kleinflächige Versuchsflächen (<1 ha) nicht ausreichten, um waldbauliche Behandlungen in ungleichaltrigen Mischwäldern zu beurteilen. Daher wurden bereits damals überall in den USA in zahlreichen Versuchswäldern (experimental forests) Versuchsflächen von Abteilungsgröße (10–20 ha) eingerichtet. Großflächige Feldversuche erlebten während der letzten zehn Jahre aus verschiedenen Gründen eine Renaissance: die Suche nach Alternativen zur schlagweisen Nutzung, die eine Verjüngung lichtbedürftiger Arten gewährleisten; das erneute Interesse an der Schaffung von bestandesweiser Strukturdiversität, sowie die Notwendigkeit, Hypothesen zur Biodiversität auf Bestandesebene zu testen. Großflächige Feldversuche sind kostspielig. Ihre Anlage, die zweckmäßige Anordnung von Wiederholungen, die Überwachung und der Unterhalt sind aufwändig, aber sie haben viele Vorzüge: (1) Wissenschaftler bekommen einen Eindruck von der Realität im Management, wie z.B. von den begrenzten Möglichkeiten der Holzernte-Systeme; (2) die Versuchsflächen bieten lebendige und realitätsnahe Beispiele innovativer Waldbauverfahren, die von Praktikern leichter verstanden und akzeptiert werden; (3) die installierten Messstationen sind nützliche Feldlabore, die zahlreiche Möglichkeiten zur Untersuchung von kleinskaligen Fragestellungen, wie die Verteilung von Amphibien und Sämlingen, bis zu großskaligen Bestandesreaktionen auf gut dokumentierte und fachkundig durchgeführte Waldbauverfahren bieten.

7. Résumé

Titre de l'article: *Expériences de sylviculture à long terme et sur des grandes surfaces aux U.S.A. Aspects historiques et exemples contemporains.*

Cet article concerne les expériences et les résultats des recherches de sylviculture poursuivies au champ et sur le long terme dans 4 régions des USA: au nord-est, dans la zone des grands lacs, au centre du sud et au nord-ouest, sur la côte du Pacifique. Déjà, dans les années 20 du siècle dernier, alors que partout aux U.S.A. on portait intérêt à un système de forêt durable, les forestiers s'étaient rendus compte que des petites placettes expérimentales (< 1 ha) ne suffisaient pas pour porter un jugement sur les traitements sylvicoles dans les forêts mélangées inéquiennes. En conséquence, on a installé, dès cette époque et partout aux U.S.A., des placettes expérimentales ayant la surface d'une parcelle (10–20 ha) dans de nombreuses forêts dites d'expérience (experimental forests). Ces recherches sur un terrain de grande surface ont vécu, pour diverses raisons, un véritable renouveau au cours des dernières décennies = recherche d'alternatives à la coupe à blanc assurant la régénération naturelle des essences de lumière, le désir renouvelé d'assurer une structure diversifiée aux peuplements les hypothèses à tester en ce qui concerne la biodiversité au niveau du peuplement. Ces dispositifs étendus sont coûteux. Leur installation, le programme judicieux de répétitions, la surveillance et l'entretien ont des coûts, mais les avantages sont nombreux =

1) les scientifiques acquièrent une idée de la réalité dans le management, comme par exemple des possibilités réelles des systèmes de récolte des bois;

2) les parcelles expérimentales constituent des exemples vivants et proches de la réalité de méthodes de sylviculture innovantes qui seront ainsi mieux comprises et plus facilement acceptées par les praticiens;

3) les stations de mesures qui sont installées sont d'utiles «laboratoires de terrain» qui offrent de nombreuses possibilités de recherches sur des questions qui se posent soit à petite échelle, comme la distribution des amphibiens ou des semis, soit à grande échelle lorsqu'il s'agit des réactions des peuplements à des méthodes de sylviculture bien étudiées et mises en œuvre avec compétence. J. M.

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From little things big things grow: The Warra Silvicultural Systems Trial in Tasmanian wet *Eucalyptus obliqua* forest

(With 3 Figures and 3 Tables)

By J. E. HICKEY*), M. G. NEYLAND, S. J. GROVE and L. G. EDWARDS

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Clear-felling; eucalyptus; variable retention; Tasmania; Australia; silviculture.

Kahlschlag; Eucalyptus; „variable retention"; Tasmanien; Australien; Waldbau.

1. INTRODUCTION

Tall wet eucalypt forests are unique to Australia and are its most productive forest type in terms of biomass accumulation (ASHTON and ATTIWILL, 1994). These forests occur discontinuously in areas of high rainfall from Queensland to southern Tasmania in eastern Australia, and in southwest Western Australia. Wet eucalypt forests can develop complex understories owing to the open nature of the eucalypt crowns. Wet forest eucalypts have a paradoxical relationship with fire (ASHTON, 1981) in that, under natural conditions, infrequent wildfires are needed to consume the understorey vegetation so that the shade-intolerant eucalypts are able to regenerate. The fires, which often kill the parent stand, allow the regeneration of the forest.

The wet eucalypt forests of the island of Tasmania are principally dominated by *Eucalyptus obliqua*, *E. delegatensis* and *E. regnans* (WELLS and HICKEY, 1999). Where the fire interval is less than about 100 years, the understorey is dominated by broad-leaved trees and shrubs, such as *Pomaderris apetala* and *Nematolepis squamea*, which are gradually replaced by a rainforest understorey if the fire interval increases to about 100–350 years (GILBERT, 1959). If the fire interval exceeds about 350 years, the eucalypts die out, which results in rainforest that is usually dominated by *Nothofagus cunninghamii.*

Clearfell, burn, and sow (CBS) is the prescribed silvicultural technique for wood production from wet eucalypt forests in southeastern Australia (FLORENCE, 1996). The CBS system is widely practiced in Tasmania, which is Australia's most forested State, with about 50% of its land area of 6.8 million ha being forest. Over 40% of the forest is in protected areas.

Clearfelling is defined in Tasmania as the felling of all or nearly all the trees on an area in one operation, where the minimum size of the area has a diameter of four to six times the average tree height (FOREST PRACTICES BOARD, 2000). The CBS system involves the felling of all the standing timber in coupes that average about 50 ha. The harvest residues (slash and unmerchantable wood) are reduced by high-intensity burns lit under rigidly prescribed conditions in mid-autumn. The resultant seedbed of mineral soil, exposed by burning or mechanical disturbance, is aerially sown with seed from on-site eucalypt species. Standard rotation lengths are about 90 years. The CBS system is used because it is the safest for forest workers, gives the highest financial return to the forest owner, and the slash burning maximises seedbed and eucalypt growth and removes fuel that would pose a subsequent wildfire risk (FORESTRY TASMANIA, 1998). The system has some congruence with the natural wildfire system (ATTIWILL, 1994; HICKEY, 1994; BAKER et al., 2004), but wildfires typically leave more structures such as standing trees, which, although often killed by wildfire, may also survive it (HICKEY et al., 1999; LINDENMAYER et al., 2000). The system also disturbs the minimum area of forest for a given level of wood supply (CAMPBELL, 1997a).

The CBS system raises concerns, particularly because of initial aesthetics, a reduction in late-successional species and structures (LINDENMAYER and MCCARTHY, 2002), and a decline in the special species timber resource (slow-growing noneucalypt species prized by craftworkers) when rotations of about 90 years are used. These concerns indicated a need to explore alternatives to clearfelling that are more socially acceptable, that increase the ability, or shorten the period, for the regenerated forest to return to the preharvest condition, and that are still commercially viable.

The 200-ha Warra Silvicultural Systems Trial (HICKEY et al., 2001) was established in southern Tasmania from 1998 to 2004 in multiaged 50-m-tall lowland wet *Eucalyptus obliqua*-dominated forest to compare CBS with five alternative treatments that included: (1) CBS with dispersed understorey islands that occupy <5% of the coupe area, (2) 80-m width stripfells, (3) 10–15% (basal area) dispersed retention, (4) 30% (canopy area) aggregated retention, and (5) Single-tree/small-group selection (openings < mature tree height wide). The trial is located at latitude 43°04´S, longitude 146°41´E in southern Tasmania and lies within the 15 900-ha Warra Long-Term Ecological Research (LTER) site (BROWN et al., 2001). *Figure 1* shows the location of the Warra LTER site.

Initial treatment selection was informed by the relatively few silvicultural systems that had previously been established in wet eucalypt forests in southeastern Australia, with the most significant being the Silvicultural Systems project in *Eucalyptus regnans* regrowth forest in Victoria (SQUIRE, 1990). Subsequent terminology and modification and interpretation of the treatments was informed by a developing awareness of international efforts (e.g.,

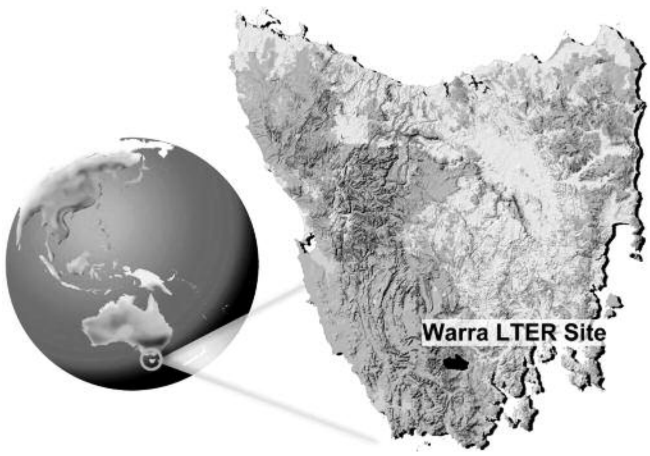

Fig. 1

Location of the Warra Long-Term Ecological Research Site in Tasmania.

Geografische Lage der langfristigen ökologischen Versuchsanlage *Warra* in Tasmanien.

*) Corresponding author: JOHN E. HICKEY, Forestry Tasmania, Australia. E-Mail: john.hickey@forestrytas.com.au

FRANKLIN et al., 1997; FRIES et al., 1997; ARNOTT and BEESE, 1997; MITCHELL and BEESE, 2002) to develop silvicultural alternatives in forest types traditionally managed for wood production by clear-felling.

This paper describes the design and objectives of the Warra Trial, preliminary results, significant outcomes for management, strengths and limitations of the trial and recommendations for others contemplating a similar investment.

2. TRIAL DESIGN AND OBJECTIVES

HICKEY et al. (2001) provided a detailed rationale for the Warra trial. The forest at the trial is multiaged owing to fires that occurred pre-1800, in 1898, and 1934 (ALCORN et al., 2001) and had not previously been harvested. Understoreys range from dense *Gahnia grandis* (cutting grass) and *Melaleuca squarrosa* (paperbark) on soils with impeded drainage to *Pomaderris apetala* (dogwood) and *Nematolepis squamea* (lancewood) on well-drained soils (NEYLAND, 2001). Long-unburnt patches have rainforest understoreys. NEYLAND et al. (2000) have shown that the tall *Eucalyptus obliqua*-dominated forests at Warra are broadly representative of this lowland wet forest type, which is Tasmania's most widespread forest type and the most important source of native forest timber.

The trial has two replicates of each treatment. Treatment descriptions, objectives, and establishment dates are summarised in *Table 1.* The single-tree/small-group selection treatment was applied at only one coupe because of significant safety, financial, and regen-

Table 1

Treatments at the Warra Silvicultural Systems Trial.

Behandlungsvarianten im Warra Waldbausystem-Versuch.

Treatment and description	Objectives	Established
Clearfell, burn, and sow (CBS) Up to 100-ha openings, 0% basal area retention, high-intensity burn, applied seed.	Efficient and safe eucalypt harvest with maximum growth of eucalypt regeneration and adequate biodiversity outcomes.	2000, 2001
CBS with understorey islands As for CBS and up to 5% of the coupe to be in dispersed 40-m by 20-m machinery-free areas.	Efficient and safe eucalypt harvest with good growth of eucalypt regeneration and enhanced local survival of understorey flora on the machinery-free areas.	2000, 2001
Stripfell (cable harvested) 250-m by 80-m strip openings, low-intensity burn, natural seedfall.	Harvest eucalypt as safely as possible with adequate growth of eucalypt regeneration and enhanced biodiversity by using strips of undisturbed forest retained for half the rotation for habitat and seed supply (all species).	2000 (2 coupes)
Dispersed retention 10-15% basal area retention, low-intensity burn, natural seedfall.	Harvest eucalypt as safely as possible with adequate growth of eucalypt regeneration and enhanced biodiversity by using individual eucalypt trees retained for a full rotation for fauna habitat and seed supply.	1998, 2000
Aggregated retention 30% of coupe retained in aggregates of 0.5 to 1.0 ha, with distance between aggregates at least twice tree height, low-intensity burn, natural seedfall.	Harvest eucalypt and special species as safely as possible, with adequate growth of eucalypt regeneration and enhanced biodiversity by using patches of undisturbed forest retained for a full rotation for habitat, seed supply (all species), and aesthetics.	2004 (2 coupes)
Single-tree/small-group selection (SGS) Retention of > 75% forest cover, permanent snig tracks, harvest 40 m^3/ha every 20 years, openings < tree height wide, heaping of slash, mechanical soil disturbance (no burning), natural seedfall.	Harvest of mature trees as safely as possible with adequate growth of eucalypt and special species regeneration, and enhanced biodiversity while maintaining a continuous tall forest cover.	2001
Group Selection (GS) Retention of 70% forest cover, permanent snig tracks, harvest 30% of the canopy cover every 30 years using groups and strips, openings twice tree height wide, low intensity burn, natural seedfall.		2006

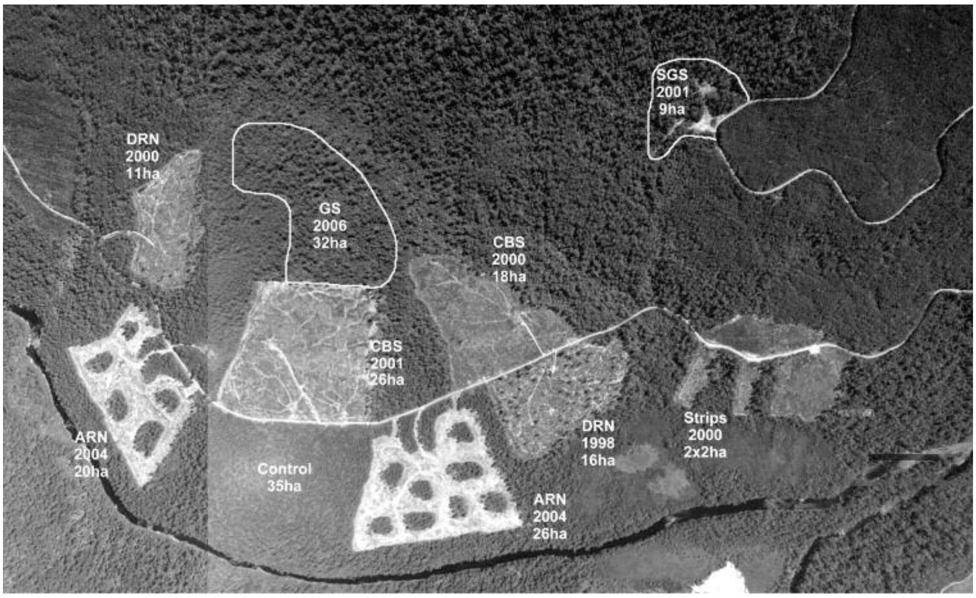

Fig. 2

An aerial view of the Warra Silvicultural Systems Trial (in 2003).
CBS = clearfell, burnt, and sown, Strips = stripfell, DRN = dispersed retention,
ARN = aggregated retention, SGS = single-tree/small-group selection and GS (planned) = group selection.
Four understorey islands are located in each of the CBS coupes.

Luftbild der Versuchsanlage *Warra* aus dem Jahr 2003.
CBS = Kahlschlag-Brand-Saat; ARN = aggregierte Retention,
SGS = Einzelbaum/Kleingruppenauswahl; GS (geplant) = femelartige Nutzung.
Vier inselartige Reste des Unterstandes befinden sich in jeder CBS Variante.

eration concerns. These became apparent soon after harvesting, so the second group-selection coupe was delayed and redesigned (see *Table 1*). Increasing the opening size from one to two tree heights across should improve safety and economics (more harvested timber), allow low-intensity burning, and promote regeneration and disposal of major slash accumulations. The second group-selection coupe will be harvested in 2006 and will not be discussed further in this paper. *Figure 2* shows an aerial view of the Warra trial.

Our design, of two replicates per treatment, was simple but well matched to our modest resources, with core research funding of about $300,000 (AUS) per year. The design was also constrained by the complexity of adjacent treatments that variously prescribed nil, low-intensity, or high-intensity burning. The establishment of treatments was protracted for several reasons including difficulties in selecting suitable harvesting contractors who were prepared to try alternatives to clearfelling in tall wet forests, poor burning weather (one CBS coupe ready for burning was deferred for a year because of early onset of prolonged autumn rains), and restricted access during construction of an adjacent tourism facility.

The treatments are being assessed against eight quantitative primary response variables (*Table 2*). Other variables, such as worker safety, have been assessed qualitatively or have been limited to a subset of treatments. Some baseline data on mammal assemblages have been collected, but further monitoring is unlikely to be very informative because the local mammalian fauna is relatively simple and abundant across all treatments. Some baseline data were also collected on water quality but comparisons between treatments would not be meaningful, as the treatments were not assigned to specific catchments. Core monitoring of worker safety, burning, tree stocking, early growth, health of retained trees, and changes in plant, invertebrate, and bird assemblages has been guided by written protocols, e.g. NEYLAND et al. (1998), BASHFORD et al. (2001) and LEFORT (2004).

Table 2

Primary response variables for the Warra Silvicultural Systems Trial.

Primäre Responsvariablen im Warra Waldbausystem-Versuch.

	Variable
Biodiversity	Vascular and nonvascular plant assemblages.
	Bird assemblages.
	Ground-active arthropod assemblages.
Silviculture	Proportion of effective seedbed.
	Seedling density and early growth of commercial trees.
	Growth and mortality of residual trees.
	Effect of browsing on eucalypt regeneration.
Social	Measurement of acceptability from simulations.
Economic	Financial effects for forest grower.

3. PRELIMINARY RESULTS

The trial has resulted in some 21 journal papers, 15 technical reports and 7 theses, which are listed on the Warra LTER site website (www.warra.com). Many of the publications describe the preharvest condition. The coupes will be formally assessed against the response variables in 2007 when all the coupes, excluding the second group-selection treatment, are at least 3 years old. However, some preliminary results are available and have been used to inform management decisions.

3.1 Safety

It is already evident that aggregated and dispersed forms of variable retention increase risk to forest workers, compared to clearfell systems, owing to the increased exposure time to limbs falling from retained trees (FORESTRY TASMANIA, 2004b). Aggregated retention is safer than dispersed retention, and risks were considered acceptable in tall eucalypt forest where the distance between aggregates was at least twice tree height (generally >80 m). Single-tree/small-group selection treatments posed the highest risk, with openings less than a tree height considered to pose an unacceptable harvesting risk when using current technologies.

3.2 Fire management

Management burns to reduce slash and create seedbed are difficult, but possible, with variable-retention systems. The fire intensity must be high enough to significantly reduce the impeding slash cover but low enough so that aggregates can be retained largely unburnt. This was achieved by burning later in autumn and under milder conditions than used for high-intensity burning. It was found that heaping of fuels by using excavators increased the effectiveness of burns conducted under very mild weather conditions. An alternative solution may become available if proposed bioenergy plants are established and provide markets for some of the currently unsaleable residues.

3.3 Eucalypt regeneration

Figure 3 shows eucalypt stocking at ages 1 and 3 for the five applied treatments. The prevailing standard is that 65% of 16 m^2 plots should be stocked with at least one eucalypt seedling by age 3 (FORESTRY TASMANIA, 2003). The CBS treatment (with understorey islands) easily met this standard at ages 1 and 3. None of the other treatments were artificially sown and therefore are reliant on natural seedfall. The nonclearfell treatments had a protracted recruitment period as shown by an increase in stocking between ages 1 and 3. The stripfells and the dispersed retention coupes substantially achieved the standard by age 3 (one dispersed retention coupe was slightly below standard), but the single-tree/small-group selection treatment fell well below the minimum standard. It is too early to predict if the aggregated retention coupes will meet the standard by age 3.

3.4 Financial effects for forest grower

The financial effect on the forest grower was studied (NYVOLD et al., 2005) by using the expectation value concept to compare the economic feasibility of the different silvicultural treatments. The expectation value is the notional income an investor would expect from an existing forest stand under the assumption that he implements a defined silvicultural system for a designated rotation length over infinite rotations. The analysis focussed solely on timber revenues and management costs and did not include nontimber values. Clearfell, burn, and sow (CBS) ranked as financially superior to all other systems at the trial. The single-tree/small-group selection treatment had the lowest economic rank. The economic analysis was dominated by the high value of the existing crop.

3.5 Social acceptability

The social acceptability of the main treatments was assessed (FORD et al., 2005) by developing computer-simulated pictures of the different systems superimposed on the same patch of forest. The pictures were shown to about 550 people, classed as either industry-affiliated, conservation-affiliated or nonaffiliated, who filled in questionnaires as they viewed the pictures. Half the participants were given information about the consequences of harvesting for fauna, forest products, and other forest values. The study found that, in the absence of information, the nonaffiliated people found clearfelling least acceptable and single-tree/small-group selection most acceptable. With information, clearfelling was still considered unacceptable, but a 30% aggregated retention system

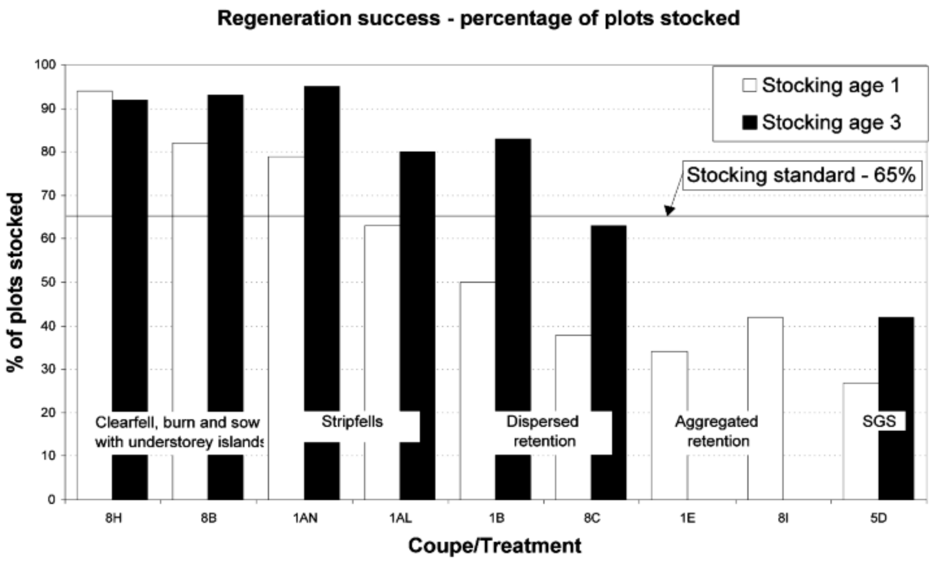

Fig. 3

Eucalypt stocking at age 1 and 3 for coupes at the Warra Silvicultural Systems Trial.
Labels on the X-axis refer to individual coupe names. SGS = single-tree/small-group selection.

Eukalyptus-Verjüngung, Bestockung im Alter 1 und 3 für die unterschiedlichen Varianten im *Warra* Experiment. Die Beschriftungen auf der X-Achse beziehen sich auf einzelne Varianten.
SGS = Einzelbaum/Kleingruppenauswahl.

was considered as acceptable as single-tree/small-group selection systems.

3.6 Biodiversity comparisons

Biodiversity comparisons among the Warra treatments are not yet available, but some recent studies in nearby routine clearfell coupes are informative. For example, TABOR (2004) studied the regeneration of four rainforest (i.e., late-successional) tree species (*Nothofagus cunninghamii*, *Eucryphia lucida*, *Atherosperma moschatum* and *Phyllocladus aspleniifolius*) in five CBS forest coupes with retained old-growth forest edges. The coupes had been burnt and regenerated between 8 and 22 years previously. *N. cunninghamii* and *E. lucida* seedling density declined from over 1300 and 2500 seedlings ha^{-1}, respectively, at 10 m from an edge, to around 30 and 70 seedlings ha^{-1} at 200 m. *A. moschatum*, which has wind-dispersed seed, was more abundant than *N. cunninghamii* and *E. lucida* in plots greater than 20 m from an edge. More than 500 *P. aspleniifolius* seedlings ha^{-1} were found at all distances from the coupe edge and probably result from a capacity to germinate from soil-stored and bird-dispersed seed. The study concluded that in the absence of further disturbance, an old-growth mixed forest of eucalypts and rainforest trees would eventually reform but aggregated retention, with aggregates less than 100 m apart, potentially offered a more rapid succession toward the preharvest condition.

Preharvesting studies within the Warra trial have compared the beetle, bryophyte, lichen, and fungal diversity of regrowth trees (from non-stand-replacing fires in 1898 and 1934) with veteran old-growth trees, which are well over 150 years old. KANTVILAS and JARMAN (2004) found a general trend of increasing richness of bryophyte and lichen species with increasing tree diameter. HOPKINS et al. (2005) found that old-growth trees support more beetle and fungal species than do regrowth trees.

4. MANAGEMENT IMPLICATIONS

In 2001, the Tasmanian government facilitated a community process called Tasmania Together (COMMUNITY LEADERS GROUP, 2001), which identified goals and targets for a range of social, environmental, and economic indicators. One of the targets was that clearfelling of old-growth forest would end by 2010. Although the targets were nonbinding, the government sought advice on alternatives to clearfell silviculture for old-growth forest on public lands designated for wood production. Preliminary results from the Warra trial were a key input into that advice (FORESTRY TASMANIA, 2004a). *Table 3* summarises the probable management implications of the major alternatives when applied at the coupe level by using a rank-based assessment in six key management areas. In 2005, the Tasmanian and Australian governments agreed that nonclearfell methods would be adopted for 80% of the annual old-growth harvest by 2010 (COMMONWEALTH OF AUSTRALIA AND STATE OF TASMANIA, 2005). About five operational aggregated retention coupes will be harvested on public land in 2005, and this is planned to increase to about 20 to 30 coupes per year by 2010.

Table 3

Preliminary rankings for major alternatives to clearfelling old-growth eucalypt forest. (1 = best, 4 = worst). Abbreviations: SGS = single-tree/small-group selection, CBS = clearfell, burn, and sow. (from FORESTRY TASMANIA, 2004a)

Vorläufige Rangordnung der wichtigsten Alternativen zum Kahlschlag alter Eucalyptuswälder (1 = beste, 4 = schlechteste Variante). Abkürzungen: SGS = Einzelbaum/Kleingruppenauswahl, CBS = Kahlschlag-Brand-Saat (aus FORESTRY TASMANIA, 2004a).

	CBS	Dispersed retention	Aggregated retention	SGS
Productivity	1	3	2	4
Operability	1	3	2	4
Worker safety	1	3	2	4
Fire safety	1	3	2	4
Biodiversity	4	3	1-2	1-2
Acceptability	4	3	1	1

The increased adoption of the aggregated form of variable retention poses management challenges for worker safety, fire management, and regeneration as well as for containing costs of planning and harvesting. The implementation of variable retention may be easier if there is greater utilisation of harvest residues, most likely as fuelwood for proposed power stations. However, it is recognised that it will be important to maintain sufficient levels of coarse woody debris so that critical habitat for log-dependent fauna is maintained (GROVE and MEGGS, 2003).

Many of the challenges in implementing variable retention have been encountered, and at least partially resolved, in tall old-growth forests elsewhere (eg., BEESE et al., 2003). Hence, there is great potential for increased networking of research and operational findings across jurisdictions to assist in the development of optimal approaches. However, variable retention in tall old-growth eucalypt forests incurs particular challenges associated with the dense understoreys of trees and shrubs that develop under eucalypt canopies: the irregular shape of the eucalypt tree crowns and the consequent large volumes of harvest residues that can accrue in fire-prone landscapes (HICKEY and BROWN, 2003).

5. WEAKNESSES AND STRENGTHS OF THE WARRA TRIAL

Despite its considerable impact and influence, the Warra trial has weaknesses, primarily owing to the usual limitations on funds and resources in a moderate sized commercial organisation. The trial is confined to a single site with only two replicates per treatment. The allocation of treatments to coupes at Warra was not random; instead it took into account vegetation attributes to test particular treatments. Hence, stripfell and single-tree/small-group selection treatments were allocated to coupes with a high proportion of rainforest understoreys, as they were primarily designed to test mixed eucalypt-rainforest regeneration. This raises concerns regarding the statistical scope of inference of trial results to large forest areas (GANIO and PUETTMANN, 2004). The treatments have also been implemented over a protracted period of 6 years (excluding the second group selection treatment). Hence, there is also uncertainty on the effects of seasonal variation on outcomes.

Even so, the Warra trial is significant at least at a national scale (e.g., LINDENMAYER and FRANKLIN, 2002), as one of only two major silvicultural systems trials in tall wet eucalypt forests, the other being a silvicultural systems trial at Tanjil Bren in Victoria (CAMPBELL, 1997b). Strengths of the Warra trial include the following: the forest had never previously been harvested, which avoids uncertainties arising from past intervention; the trial has extensive internal and remote control sites to provide benchmarks; and, coupes have been implemented in similar ways and sizes to those used operationally. There is also a synergy between research undertaken at the trial and research findings from the surrounding Warra LTER site. For example, biodiversity outcomes from the silvicultural treatments can be compared with wildfire reference sites that are currently being established in the surrounding landscape. Over time, these comparisons should indicate the degree of congruence of various silvicultural treatments with natural wildfire systems.

The Warra trial is proving a sound research investment, at some $300,000 (AUS) annually, in that it has fostered interaction among forest workers, researchers, managers, and policy makers and has been instrumental in developing new silvicultural approaches for wet eucalypt forests, particularly for old-growth wet forests. The trial, and the surrounding LTER site, has also provided a medium for potential participation in international research workshops and networks, such as that developed by PETERSON and MAGUIRE (2004).

The future of the Warra trial appears sound. Additional funding has been secured to fully evaluate the performance of the alternatives in 2007 when all treatments (except the second group selection treatment) will be at least 3 years old. Ongoing assessments of growth and biodiversity are planned when treatments are aged 10 years and then at 10-year intervals thereafter. No single trial or study site can provide answers to all the complex ecological, economic, and social questions asked of forest managers. However, the results gained at Warra can be interpreted alongside outcomes from operational coupes and with similar long-term silvicultural sites established elsewhere to increase confidence in research outcomes. The trial is also developing considerable public interest with some 300 visitors being guided through the site each year. There is potential for increased visitation and interpretation of the trial owing to its proximity to a major forest tourism attraction, the Tahune AirWalk, which attracts over 100,000 visitors per year.

6. RECOMMENDATIONS FOR THOSE CONSIDERING SIMILAR MULTIDISCIPLINARY LONG-TERM TRIALS

From our experience, we would encourage others to invest in multidisciplinary long-term experiments that investigate the effects of silvicultural systems. However, such investments are expensive and require long-term resources (POWERS, 1999). Such an investment is only justified if there is a willingness to consider alternative practices. One of the key measures of success for any silvicultural systems trial should be an increase in understanding of the costs and benefits of a range of silvicultural treatments over a range of disciplines. The uptake of alternative treatments may well be desired, but is not an essential outcome of the research.

It may be important to choose sites with some visitor potential to maintain interest and funding commitment. In our case this should be achieved by our location close to the spectacular Huon River, the Tahune AirWalk, and the eastern portion of the Tasmanian Wilderness World Heritage Area. Of course, it is important to seek best statistical practice (BENNETT and ADAMS, 2004), and this would imply that multiple locations be used, if resources permit, and that sites are broadly representative. We have found that there will be inevitable tradeoffs between best statistical practice and the realities of implementing a large-scale experiment in complex natural and administrative environments. We feel it is important to find a balance between design standards and logistic constraints and not to falter at the inevitable statistical difficulties.

We have found it useful to maximise interest and usage of our trial by offering an "open door" to potential collaborators who wish to use the trial, or subcomponents, for their own research purposes. A modest research grant program has assisted this. Finally we recommend a strong communication effort through scientific publication, guided visits, websites, and the popular media.

7. ABSTRACT

Clearfell, burn, and sow (CBS) is the most efficient silvicultural system for the regeneration of wet eucalypt forests in southeastern Australia but it raises concerns because of aesthetics and a reduction in late-successional species and structures when rotations of 90 years are used. The 200-ha Warra Silvicultural Systems Trial was established from 1998 to 2004 in Tasmanian multiaged wet *Eucalyptus obliqua*-dominated forest to compare CBS with five alternatives: (1) CBS with dispersed understorey islands that occupy <5% of the coupe area, (2) 80-m width stripfells, (3) 10–15% (basal area) dispersed retention, (4) 30% (canopy area) aggregated retention, and (5) Single-tree/small-group selection (openings <45 m across). Our design, of two replicates per treatment, was simple but well matched to our modest research funding. Despite some limitations, the trial has been instrumental in developing silvicultural approaches for wet eucalypt forests, particularly for wet old-growth forests. In 2005, the Tasmanian and Australian Governments agreed that non-clearfell methods would be used for 80% of the annual old-growth harvest on public land in Tasmania by 2010. The Warra trial has also provided a medium for participation in international research networks.

8. Zusammenfassung

Titel des Beitrages: *Kleine Anfänge mit großer Wirkung: Der waldbauliche Feldversuch Warra in einem feuchten Eucalyptus obliqua Wald in Tasmanien.*

Das Kahlschlagverfahren mit anschließendem Verbrennen des Schlagabraums und künstlicher Saat ist die wirkungsvollste Verjüngungsmethode für die feuchten Eukalyptuswälder im Südosten Australiens. Dieses Verfahren wird kritisch beurteilt, besonders wenn es für Umtriebszeiten von 90 Jahren praktiziert wird. Die Waldästhetik wird beeinträchtigt. Ausserdem ergibt sich eine geringe strukturelle Vielfalt und ein eingeschränkter Artenreichtum in den späten Sukzessionsstadien. Der 200 ha große Feldversuch *Warra* wurde im Zeitraum 1998 bis 2004 in einem feuchten *Eucalyptus obliqua* Wald eingerichtet, um das Kahlschlagverfahren mit fünf waldbaulichen Alternativen zu vergleichen: 1. Kahlschlag mit inselartigem Erhalt der Unterschicht auf weniger als 5% der Schlagfläche, 2. streifenweise 80m breite Schlagflächen, 3. Kahlschlag mit Erhalt verstreuter Einzelbäume (10–15% der Grundfläche), 4. Erhalt von inselartigen Bestandesresten auf 30% der Fläche, 5. Einzelstammweise Nutzung und Lochhiebe mit einem Durchmesser von höchstens 45 m. Das Versuchskonzept war mit 2 Wiederholungen pro Behandlung relativ einfach und angepasst an das begrenzte Forschungsbudget. Trotz dieser Einschränkungen hat dieser Versuch einen fundamentalen Einfluss auf die Entwicklung waldbaulicher Verfahren für die feuchten Eukalyptuswälder gehabt, insbesondere in den sehr hochgewachsenen „Oldgrowth"-Wäldern. Die Regierungen von Tasmanien und Australien trafen im Jahr 2005 die Vereinbarung, dass bis zum Jahr 2010 das typische Kahlschlagverfahren auf 80% der jährlichen Schlagfläche in „Oldgrowth"-Wäldern durch alternative Verfahren ersetzt wird. Der Warra-Versuch hat dem Forschungsteam die Teilnahme an internationalen Forschungs-Netzwerken ermöglicht.

9. Résumé

Titre de l'article: *Petits débuts grands effets le dispositif de recherches de sylviculture WARRA dans une forêt humide d'Eucalyptus obliqua en Tasmanie.*

La méthode de la coupe à blanc associée à l'incinération des rémanents d'exploitation puis à un semis artificiel assure efficacement la régénération dans les forêts humides d'eucalyptus du sud-est de l'Australie. Ce procédé est soumis à critiques, tout particulièrement lorsqu'il est appliqué pour les rotations de 90 ans. Il est ainsi porté préjudice à l'esthétique des forêts. De surcroît cela entraîne une faible variabilité structurelle et une richesse étriquée en espèces dans les stades ultérieures de la succession. Le dispositif expérimental de WARRA qui couvre 200 ha a été installé dans la période de 1998 à 2004 dans une forêt humide *d'Eucalyptus obliqua* pour comparer cinq variantes sylvicoles de la coupe à blanc: 1) coupe à blanc avec maintien en îlots du sous-étage sur moins de 5% de la surface; 2) coupe en bandes de 80 m de large; 3) coupe à blanc, mais en conservant toutefois quelques arbres isolés (10 à 15% de la surface terrière); 4) maintien sous forme d'îlots du peu-

plement sur 30% de la surface; 5) exploitation pied à pied et coupe par trouées d'un diamètre maximal de 45 m.

Le protocole expérimental prévoyait 2 répétitions par traitement; il était donc relativement simple, ce qu'impliquait le budget limité alloué à la recherche. Malgré les contraintes financières, cette expérience a eu une influence fondamentale sur l'évolution des méthodes sylvicoles applicables aux forêts humides d'eucalyptus, tout particulièrement aux forêts «Oldgrowth» à croissance très rapide. Les gouvernement d'Australie et de Tasmanie prirent en 2005 la décision que jusqu'en 2010 et sur 80% de la surface exploitée annuellement dans les forêts «Oldgrowth» la méthode typique de coupe à blanc serait remplacée par des procédés alternatifs. L'expérience de WARRA a ainsi permis à l'équipe de chercheurs de faire partie du réseau international de recherches forestières. J. M.

10. Date and address

Draft paper submitted on 11 October 2005 and revised paper submitted on 11 Jan 2006 by JOHN HICKEY, Forestry Tasmania, 79 Melville Street, Hobart, Tasmania, Australia 7000.

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Stand dynamics after variable-retention harvesting in mature Douglas-Fir forests of Western North America[1)]

(With 9 Figures and 4 Tables)

By D. A. MAGUIRE[2),*)], D. B. MAINWARING[2)] and C. B. HALPERN[3)]

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Biodiversity; stand structure; mortality; regeneration; advance regeneration.

Biodiversität; Bestandesstruktur; Mortalität; Verjüngung.

1. INTRODUCTION

Variable-retention has been proposed as a way to mitigate the effects of timber harvest on biological diversity, particularly late-seral species (FRANKLIN et al., 1997). In the context of silvicultural systems, variable-retention harvests represent a regeneration cut because the primary objective is to regenerate the stand without clearcutting. In its implementation, variable-retention bears strong resemblance to the classical system of shelterwood with reserves (MATTHEWS, 1991). Past experience with traditional systems, therefore, can help with the design of new treatments that target specific structural objectives, such as multiple cohorts and layers of trees, or control growth rates of understory trees by varying overstory density. The objectives that motivate variable retention, however, are generally more complex than those implicit in classical systems or that their variants (MITCHELL and BEESE, 2002), and little experience has accrued on ecological responses to different levels or spatial patterns of overstory retention. Even if habitat requirements of key species are known, a coarse-filter approach (HUNTER et al., 1988) that yields a diversity of vegetation structures over time and space (SEYMOUR and HUNTER, 1999) remains the most promising way to avoid erosion of forest biodiversity. Achieving this goal, however, requires understanding how forest stands will respond to a wide range of silvicultural treatments applied at spatial scales that accommodate the organisms of interest, are operationally feasible, and yield information relevant to forest management and policy.

Many questions arise about basic aspects of forest stand dynamics in designing silvicultural regimes to meet timber, aesthetic, and biodiversity objectives. Can residual overstory trees be retained without significant loss to wind damage, and if they survive, will growth accelerate or decline? How quickly does advance regeneration respond to release, and how do species differ in their responses? Do planted seedlings perform as well as, or better than, advance regeneration or newly recruited natural seedlings? For a given level of retention, how variable is the impact on tree growth among differing spatial patterns of residual trees? What are the structural outcomes of retaining differing levels and/or patterns of residual trees? Without knowledge of these responses, design of variable-retention treatments and the silvicultural systems they comprise is tentative at best.

Answers to some of these questions are suggested, in part, by past work on shelterwood systems, clearcuts with reserve trees, clearcuts in the presence of advance regeneration, overstory removals from stands with naturally established understory trees, and sanitation cuts in mature or old-growth timber. Mortality of residual trees has been shown to accelerate at least temporarily when residuals were either dispersed (BUERMEYER and HARRINGTON, 2002) or left as intact fragments (ESSEEN, 1994). The mortality rate of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) left as reserves in one clearcut was 7% over a period of 12 years (BUERMEYER and HARRINGTON, 2002), suggesting an annualized mortality rate of approximately 0.6%. Growth responses of overstory trees may be positive or negative, depending on time since harvest, species, relative canopy position, logging damage, and various other biotic and abiotic factors. Although "thinning shock" (temporary decline in diameter and/or height growth) has been observed after stand density reduction (HARRINGTON and

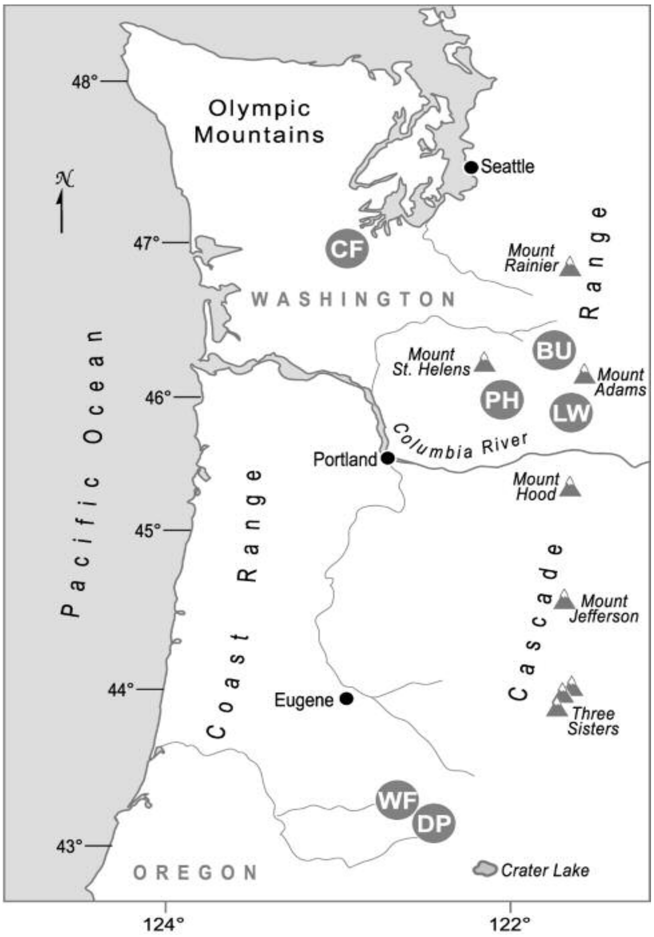

Fig. 1

Location of six DEMO blocks in Oregon and Washington, USA.

Lage der sechs DEMO Blöcke in Oregon und Washington, USA.

1) This is a product of the Demonstration of Ecosystem Management Options (DEMO) study, a joint effort of the USDA Forest Service Region 6 and Pacific Northwest Research Station. Research partners include the University of Washington, Oregon State University, University of Oregon, Gifford Pinchot and Umpqua National Forests, and the Washington State Department of Natural Resources. Funds were provided by the USDA Forest Service, PNW Research Station (PNW-93-0455 and PNW 97-9021-1-CA).

2) Department of Forest Science, Oregon State University, Corvallis, OR 97331, USA.

3) College of Forest Resources, University of Washington, Seattle, WA 98195, USA.

*) Corresponding author: DOUGLAS A. MAGUIRE.
E-Mail: Doug.Maguire@orst.edu

REUKEMA, 1983), even trees ranging in age from 160 to 650 years appear capable of responding to increases in growing space and resource availability after partial harvesting (LATHAM and TAPPEINER, 2002).

The behavior of advance regeneration after partial overstory removal will determine its contribution to the understory cohort. Thinning prior to a regeneration cut has been shown to promote establishment of advance regeneration (BUERMEYER and HARRINGTON, 2002; BAILEY and TAPPEINER, 1998), and subsequent height growth is greater under lower residual stand densities (DEL RIO and BERG, 1979; OLIVER and DOLPH, 1992; BAILEY and TAPPEINER, 1998). Overstory removal from natural two-storied stands in the Klamath Mountains of Oregon and California led to a doubling of height growth in understory Douglas-fir and white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex. Hildebr) within 5 years after release (TESCH and KORPELA, 1993). Height growth of advance regeneration on these sites compared favorably with growth of the same species in plantations, particularly on poor sites (KORPELA et al., 1992). Growth of advance regeneration generally improves with greater removal of the overstory (GRANHUS and BRÆKKE, 2001; PAGE et al., 2001; TENG et al., 2003) and with greater distances from intact forest edge (HAWKINS et al., 2002). Similarly, height growth rates of seedlings that establish after harvest typically decline with increasing overstory density (WILLIAMSON and RUTH, 1976; NILSON and LUNDQVIST, 2001); with proximity to seed trees (MCDONALD, 1976; VALKONEN et al., 2002); or with declining opening size in group selection cuts (MCDONALD and ABBOTT, 1994). Comparable responses have been documented for planted seedlings of many conifer and broadleaved species (SUZUKI et al., 1996; DIGNAN et al., 1998; COATES, 2000; BRANDEIS et al., 2001; MITCHELL, 2001).

Relatively few studies have taken a long-term, comprehensive view of the dynamics of residual trees, advance regeneration, planted seedlings, and new germinants. Such studies are needed in the Douglas-fir region of the western United States where, despite little experience with producing and maintaining two-aged or multi-aged stands of Douglas-fir, the Northwest Forest Plan mandates a minimum of 15% retention in harvest units on federal land (TUCHMANN et al., 1996). The Demonstration of Ecosystem Management Options (DEMO) study was initiated as a regional experiment to test the roles of level and pattern of overstory retention under the dual objective of conserving biodiversity and ensuring regeneration and acceptable growth of timber species. The specific objective of this analysis was to test the effect of alternative variable-retention treatments on (1) mortality and volume growth of overstory trees, (2) mortality and recent height growth of planted seedlings, and (3) recent height growth and initial response to release of advance regeneration.

2. METHODS

2.1 Study Sites and Treatments

Six study locations (blocks) were selected to represent mature (65- to 170-yr-old) forests dominated by Douglas-fir (AUBRY et al., 2004) (*Fig. 1*). Two blocks were located in the Cascade Range in central Oregon, three in the Cascade Range in southern Washington, and one in the Coast Range in southwestern Washington (43°20'N to 47°00'N latitude and 121°50'W to 123°20'W longitude). Elevations ranged from ca. 200–1700 m and slopes varied from gentle to steep, with a broad range of aspects represented (*Table 1*). Three blocks (Butte, Capitol Forest, and Watson Falls) were in the western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) forest zone, one (Little White Salmon) was in the grand fir (*Abies grandis* (Dougl. ex. D. Don) Lindl.) zone, one (Dog Prairie) was in the white fir zone, and one (Paradise Hills) was in the Pacific silver fir (*Abies amabilis* Dougl. ex Forbes) zone (FRANKLIN and DYRNESS, 1973). Total stand basal area and tree density (breast height diameter ≥ 5 cm) ranged from 47 to 89 $m^2\ ha^{-1}$ and 345 to 1147 trees ha^{-1}, respectively (*Table 2*). The climate of the region is maritime with warm, dry summers and cool, wet winters. Most of the precipitation falls between October and April, with annual precipitation ranging from approximately 800 to 2500 mm (FRANKLIN and DYRNESS, 1973).

Table 1

Topographic features, forest attributes, and harvesting and planting dates for each of the six experimental blocks in the DEMO study. Minimum and maximum values represent treatment unit means.

Topografische Einzelheiten, Eigenschaften der Waldgebiete, sowie Nutzungs- und Pflanzdaten der sechs Versuchsblöcke in der DEMO Studie. Die Maximal- und Minimalwerte beziehen sich auf die Mittelwerte der Behandlungseinheiten.

Location/ Block	Elevation (m)	Slope (%)	Aspect	Age (yr)	Site index (m at 50 yr)	Harvest date	Planting date
Oregon:							
Umpqua National Forest							
Watson Falls	945-1310	4-7	flat	110-130	30-33	7/1998	5/1999
Dog Prairie	1460-1710	34-62	SW	165	30	8/1998	5/1999
Washington:							
Gifford Pinchot NF							
Butte	975-1280	40-53	E-SE	70-80	27-32	6/1997	5/1998
Little White Salmon	825-975	40-60	NW-NE	140-170	30	6/1998	6/1999
Paradise Hills	850-1035	9-33	variable	110-140	26-33	8/1997	5/1998
Dept of Natural Resources							
Capitol Forest	210-275	28-52	variable	65	37-41	2/1998	2/1999

Table 2

Average overstory conditions in the six experimental blocks prior to harvest.

Durchschnittswerte für den Oberstand in den sechs Versuchsblöcken vor dem Eingriff.

Attribute	Watson Falls	Dog Prairie	Butte	Little White Salmon	Paradise Hills	Capitol Forest
Douglas-fir						
Tree density (no. ha^{-1})*	246	219	798	124	191	232
Basal area (m^2 ha^{-1})	34.0	73.9	50.1	66.4	39.7	56.4
Quadratic mean diameter (cm)	43	66	29	83	52	57
Stand density index†	547	1001	944	823	590	815
Stem volume (m^3 ha^{-1})‡	502	1181	567	1211	511	936
Other conifers						
Tree density (no./ha)	144	126	348	37	551	94
Basal area (m^2 ha^{-1})	13.4	15.1	5.8	3.6	33.3	4.7
Quadratic mean diameter (cm)	31	40	16	32	28	26
Stand density index	229	250	142	62	631	93
Stem volume (m^3 ha^{-1})	224	238	50	55	399	56
All species						
Tree density (no. ha^{-1})	397	345	1147	237	742	362
Basal area (m^2 ha^{-1})	47.4	89.0	56.0	70.7	73.1	64.1
Quadratic mean diameter (cm)	39	58	26	63	36	48
Stand density index	786	1269	1105	978	1259	985
Stem volume (m^3 ha^{-1})	750	1423	613	1269	903	1040

* Trees with diameter > 5 cm...
† REINEKE (1933).
‡ Based on equations from BRACKETT (1973).

At each block, five harvest treatments and a control were randomly assigned to 13-ha experimental (treatment) units (*Fig. 2*). Treatments differed by the level (percentage of initial basal area) and spatial pattern (dispersed vs. aggregated) of retained trees as follows: (1) 100%: 100% retention (control); (2) 75%A: 75% aggregated retention (three circular, 1-ha patch cuts in an uncut matrix); (3) 40%D: 40% dispersed retention (uniform spatial distribution of residual trees); (4) 40%A: 40% aggregated retention (five circular 1-ha forest aggregates in a cut matrix); (5) 15%D: 15% dispersed retention (uniform distribution of residual trees); and (6) 15%A: 15% aggregated retention (two circular 1-ha forest aggregates in a cut matrix). Residual trees in the dispersed treatments were selected from larger and more wind-stable dominants and co-dominants. The 75%A treatment was excluded from the present analysis.

Treatment units were logged by a skyline cable system (Capitol Forest), ground-based system (Watson Falls, Paradise Hills), or helicopter (Dog Prairie, Butte, Little White Salmon) (HALPERN and MCKENZIE, 2001). Harvesting in all treatment units was completed in 3–7 mo at each block (*Table 1*), and damage to residual stems was generally low (MOORE et al., 2002). Residual basal areas ranged from 8 to 100 m^2 ha^{-1} (*Fig. 3*). At one block (Watson Falls), logging slash was piled away from vegetation sampling points and burned to reduce fuel loadings to permissible levels. Logging slash was left untreated at the remaining blocks. Harvested portions of all treatment units within a block were planted with the species mix most likely to lead to reforestation success (*Table 3*). Target planting densities on the harvested portions of individual treatment units ranged from 476–741 seedlings ha^{-1} (HALPERN et al., 2005), and the species mix was predominantly Douglas-fir with one to four additional species (except Capitol Forest). Species mixes and planting densities were chosen to promote natural regeneration but to ensure adequate stocking through planting (AUBRY et al., 1999).

2.2 Plot and Tree Measurements

Overstory and understory trees were sampled in each treatment unit by using a systematic grid of points (8 x 8 or 9 x 7 with 40-m spacing of grid points; AUBRY et al., 1999). In the control and dispersed-retention treatments, 32 permanent plots were placed systematically at alternate grid points for the pre-harvest inventory. The aggregated treatments were characterized by two distinct post-harvest conditions (cut and uncut), so plots were placed at all five grid points within each aggregate (40%A and 15%A), and at a subset of points in the surrounding matrix. This design resulted in 36 or 37 plots in 40%A and 32 plots in each of the other treatments. Pre-harvest overstory conditions were sampled between 1994 and 1996 with nested circular plots: 0.01 ha for trees with diameter at breast height (D) of 5–15 cm, and 0.04 ha for larger trees. Within each plot, species and diameter (nearest 1 cm) were recorded for each tree. Total height and height to crown base were measured on a subsample of trees of each species within each treatment unit; if fewer than 40 trees were available for a given species, all individuals were measured.

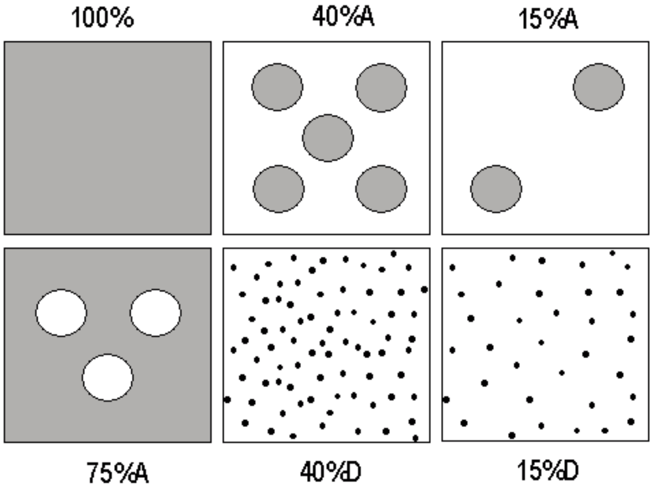

Fig. 2

Schematic diagram of DEMO variable-retention harvest treatments imposed on 13-ha treatment units. (1) 100%: 100% retention (control); (2) 75%A: 75% aggregated retention; (3) 40%D: 40% dispersed retention; (4) 40%A: 40% aggregated retention; (5) 15%D: 15% dispersed retention; and (6) 15%A: 15% aggregated retention

Schematisches Diagramm der DEMO-Behandlungen mit der Bezeichnung „variable retention harvest“ (Variable Retention), die in 13-ha Versuchseinheiten implementiert wurde. (1) 100% Retention (Kontrolle; kein Eingriff); (2) 75%A: 75% aggregierte Retention; (3) 40%D: 40% verteilte Retention; (4) 40%A: 40% aggregierte Retention; (5) 15%D: 15% verteilte Retention; and (6) 15%A: 15% aggregierte Retention.

Post-harvest overstory conditions were sampled with a 0.04-ha circular plot for all trees with D ≥ 5 cm. Sampling intensity was increased to all 63 or 64 grid points in the dispersed treatments (where tree densities were greatly reduced), but remained the same in the others. During the growing season after harvest (1998 or 1999), an aluminum tag was nailed to each tree at breast height, and species and diameter (nearest 0.1 cm) were recorded. In the same plot, all planted trees were tagged and measured for total height (nearest cm) (1998 for Butte, 1999 elsewhere).

Overstory trees were assessed for mortality annually for 2–3 years (1999 or 2000 to 2001, reflecting different harvest dates among blocks), and again in 2003. Diameter of all live trees was also remeasured in 2003 to assess growth over the 4- or 5-year remeasurement interval. Height and height to crown base (nearest 0.1 m) were measured on a subsample of 40 trees of each species within each treatment unit (or all trees if there were fewer than 40). Planted trees were also measured in 2003 for 2002 height growth (nearest 0.1 cm), and tree condition was recorded.

Growth of advance regeneration was measured in 2003 at only two blocks, Watson Falls and Paradise Hills. Advance regeneration was uncommon at the remaining blocks. Within each plot, saplings (D < 5 cm, height > 10 cm) of the primary species, Douglas-fir and true firs (*Abies* spp.), were tallied by species on 1x6 m strip plots along four perpendicular radii starting 4 m from the center of each 0.04-ha circular plot. Small saplings (≤1.5 m) were tallied by species and height class (0.1–0.2 m, 0.2–0.5 m, 0.5–1.0 m, and >1.0–1.5 m). One sapling (height <1.5 m) of each species and size class was then tagged and measured for annual height growth (nearest 0.1 cm) in 2002 and in previous years as far back as branch whorls and bud scale scars allowed.

2.3 Statistical Analysis

DEMO was designed as a completely randomized block experiment, so treatment effects were tested by ANOVA, or in some cases ANCOVA (STEEL and TORRIE, 1980). For overstory and advance

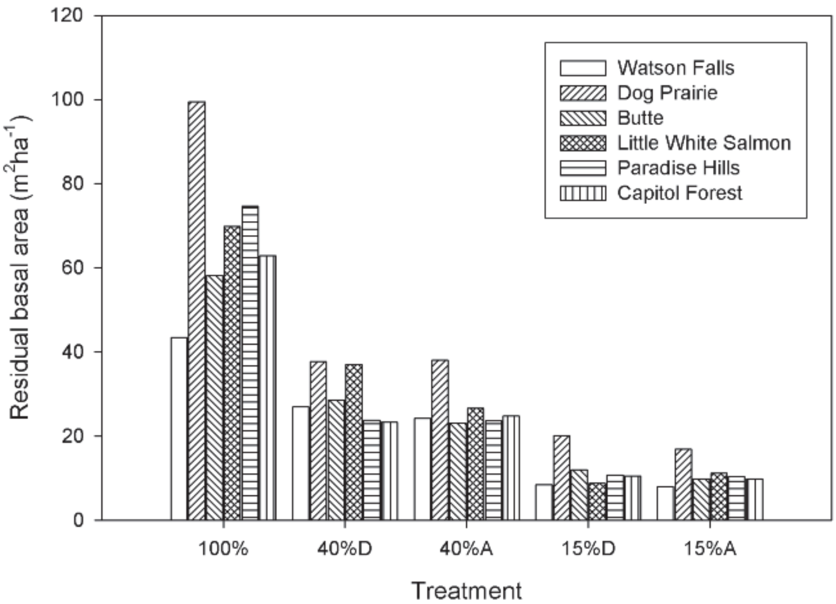

Fig. 3

Residual basal area immediately after harvest in each treatment unit and block.

Grundfläche des verbleibenden Bestandes unmittelbar nach der Nutzung in jeder Versuchseinheit und jedem Block.

Table 3

Mean density (trees ha^{-1}) of planted seedlings in the harvested portions of treatment units within each DEMO block, estimated from the number of tagged seedlings in 1998 or 1999.

Mittlere Dichte (Bäume pro ha) der gepflanzten Jungpflanzen in den geernteten Bereichen der Behandlungseinheiten innerhalb der DEMO Blöcke, geschätzt aufgrund der in den Jahren 1998 oder 1999 markierten Jungpflanzen.

Block	*Pseudotsuga menziesii*	*Pinus monticola*	*Pinus ponderosa*	*Abies magnifica*	*Abies procera*	*Abies amabilis*	*Thuja plicata*	*Tsuga heterophylla*	All species
Watson Falls	199	84	160	0	0	0	0	0	443
Dog Prairie	353	74	0	99	0	0	0	0	526
Butte	343	40	0	0	0	0	0	0	383
Little White Salmon	222	54	38	0	29	0	0	0	343
Paradise Hills	179	37	0	0	58	0	46	21	341
Capitol Forest	604	0	0	0	0	0	0	0	604

regeneration responses, treatment effects (4 df) were decomposed into four orthogonal contrasts: (1) harvest vs. control; (2) level of retention (40% vs. 15%); (3) pattern of retention (dispersed vs. aggregated); and (4) interaction of level and pattern. Because the control was not planted, treatment effects (3 df) on mortality and growth of planted seedlings were decomposed into only the last three orthogonal contrasts. All statistical tests were performed at $\alpha = 0.05$ unless otherwise noted, but p-values in the range 0.051 to 0.10 were considered marginally significant.

Annualized periodic mortality of overstory trees was expressed as a proportion of live trees tagged immediately after harvest. Only trees killed directly by wind or wet snow (stem break or uprooting) were included. Treatment effects on mortality were tested by ANOVA on the arcsin square root of this proportion, with separate tests for Douglas-fir and all other species combined.

Total stem volume of overstory trees was estimated with regional volume equations. Missing heights were filled in with a set of height-diameter equations fitted to the height subsample for each treatment unit and constrained to maintain consistency with expected height growth of the dominant Douglas-fir (Bruce, 1981; Hann and Scrivani, 1987). In addition to the randomized block ANOVA, treatment effects on total overstory volume growth were assessed by randomized block ANCOVA with initial post-treatment volume as the covariate. The ANCOVA was repeated for the volume growth of only the 25 largest trees per ha. The latter focus on dominant-codominant trees ensured that the growth of residual trees was assessed relative to the same stand component across all treatments, including the control. Overstory growth was assessed for all species combined.

Annualized periodic mortality of planted seedlings was expressed as a proportion of seedlings planted. The ANOVA was performed on the arcsin square root of annualized mortality rate for four separate species (or species groups) – Douglas-fir, ponderosa pine (*Pinus ponderosa* Dougl. ex. Laws), western white pine (*Pinus monticola* Dougl. ex D. Don), and noble fir (*A. procera*, Rehd)./Shasta red fir (*A. magnifica* var. *Shastensis*, A. Murr). Treatment effects on 2002 height growth of undamaged planted seedlings were tested by ANOVA on the same species/species groups.

Average annual (2002) height growth of advance regeneration was similarly tested by randomized block ANCOVA, with average initial tree height of the treatment unit as a covariate (0.2–1.5 m in 2001). The statistical power of the analysis was low because only two blocks had sufficient advance regeneration to be included, and the analysis was limited to two species groups that occurred in sufficient abundance, Douglas-fir and two true fir species, Pacific silver fir and white fir.

Sudden exposure of advance regeneration after overstory removal can sometimes cause "shock" or temporary reduction in height growth and, at other times, in rapid release (increase in height growth). A release index was computed as the ratio of height growth during the first growing season after treatment to height growth during the previous growing season. Treatment effects were tested by ANOVA on the average release index of all trees from the control units and from only harvested areas in other treatments (i.e., no trees from the aggregates in 40%A and 15%A). Only the true firs (*Abies* spp.) had a sufficient number of individuals with height growth identifiable back to 1997. As with height growth, the availability of only two blocks limited the power of this test.

3. RESULTS

3.1 Overstory Trees

Across all blocks and treatments, 111 Douglas-fir trees were uprooted or broken off from wind or snow loading. Overstory mortality attributable to this cause was higher for this species in harvested than in control units ($p = 0.007$), and was significantly higher in 15% vs. 40% retention ($p < 0.0001$). The interaction between level and pattern was significant ($p = 0.007$) because Douglas-fir mortality was similar in the aggregated and dispersed treatments at 40% retention, but much greater for the dispersed treatment at 15% retention (*Fig. 4*). For all other species combined, average annualized mortality in the control was not significantly different from that in harvested treatments. However, both level and pattern had significant effects ($p = 0.0066$, $p = 0.014$; *Fig. 4*). In 15%D, annualized mortality from wind and snow damage reached 0.65% yr^{-1} for Douglas-fir and 1.15% yr^{-1} for all other species combined (*Fig. 4*). Overstory mortality rates for the other treatments were <0.2% for Douglas-fir and <0.3% for all other species combined.

As expected, total stem volume growth of the overstory was proportional to level of retention in the ANOVA (*Fig. 5a*), so initial volume was a very significant covariate in the ANCOVA (no significant interaction with treatment). However, initial volume did not account for the greater volume growth per unit initial volume in dispersed vs. aggregated treatments ($p = 0.036$; *Fig. 5b*). Volume growth per unit initial volume for the 25 largest trees ha^{-1} was not affected by either level or pattern of retention, although harvest was marginally significant ($p = 0.085$; *Fig. 5c*).

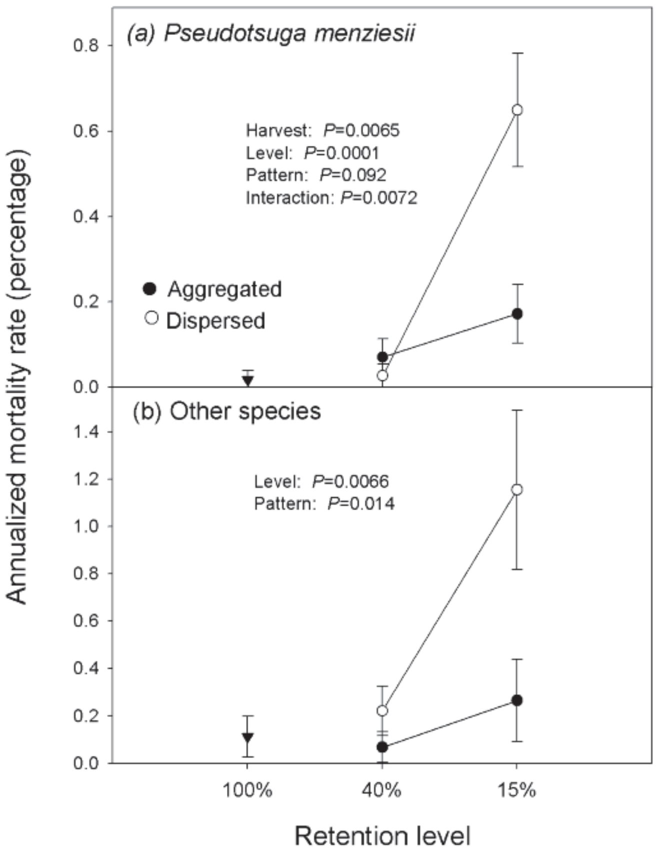

Fig. 4

Annualized mortality rate (±1 SE) of residual overstory trees by treatment and species/species group, expressed as a proportion of initial live trees.

Jährliche Mortalitätsrate (±1 SE) der verbleibenden Bäume im Oberstand für unterschiedliche Behandlungen und Baumarten/Baumartengruppen, als Anteil der ursprünglich lebenden Bäume.

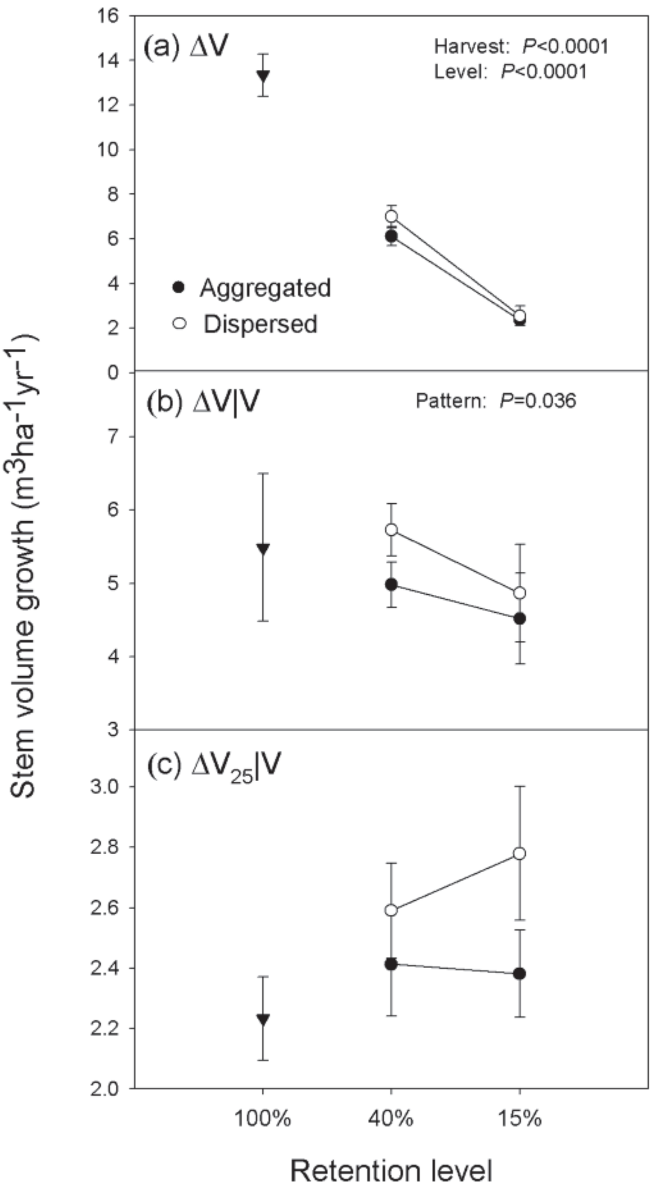

Fig. 5

Average volume growth (± 1 SE) of residual overstory trees by treatment for: (a) all trees without correction for initial stand volume (ΔV), (b) all trees with correction for initial stand volume (ΔV|V), and (c) the largest 25 trees ha^{-1} with correction for initial volume ($\Delta V_{25}/V$).

Durchschnittlicher Volumenzuwachs (ΔV; ±1 SE) der verbleibenden Bäume im Oberstand, getrennt nach Behandlungen für: (a) alle Bäume ohne Abgleich mit dem ursprünglichen Bestandesvorrat (ΔV), (b) alle Bäume mit Abgleich mit dem ursprünglichen Bestandesvorrat (ΔV|V), und (c) die größten 25 Bäume pro ha mit Abgleich mit dem ursprünglichen Bestandesvorrat ($\Delta V_{25}/V$).

3.2 Planted Seedlings

Annualized mortality of planted seedlings varied from 1 to 14% among treatment units, with greatest mortality in the true firs (noble fir and Shasta red fir) and least in ponderosa pine (*Fig. 6*). Ponderosa pine mortality was significantly less in 15% vs. 40% retention ($p < 0.035$; *Fig. 6c*). In contrast, mortality of Douglas-fir seedlings did not differ among treatments (*Fig. 6d*). In western white pine, the marginally significant effect of pattern ($p = 0.063$) and slightly insignificant effect of its interaction with level ($p = 0.106$) reflected the significantly greater mortality in aggregated vs. dispersed patterns at 40% retention, and the lack of significant difference between aggregated and dispersed treatments at 15% retention (*Fig. 6b*). In the true fir species, mortality was significantly greater under aggregated treatments ($p = 0.0043$; *Fig. 6a*), but the smaller difference between aggregated and dispersed patterns at 15% retention led to a marginally significant interaction effect ($p = 0.084$).

Average height growth of planted trees in 2002 ranged from 6 to 21 cm, and was greatest for ponderosa pine and least for noble fir/red fir (*Fig. 7*). Height growth for true fir was significantly greater in 15% than in 40% retention ($p = 0.030$), but pattern had no significant effect ($p = 0.13$; *Fig. 7a*). In both western white pine and Douglas-fir (*Fig. 7b, d*), height growth was significantly greater in aggregated vs. dispersed treatments at 40% retention, but the effect of pattern was much greater at 40% retention, resulting in a significant interaction effect on western white pine ($p < 0.015$). Height growth in ponderosa pine was marginally greater in aggregated vs. dispersed treatments ($p = 0.076$; *Fig. 7c*).

3.3 Advance Regeneration

Advance regeneration was relatively abundant at only two blocks, Watson Falls and Paradise Hills (*Table 4*). Average height growth in 2002 (representing the fourth or fifth growing season after harvest) ranged from 2 to 12 cm for true fir (white fir and Pacific silver fir) and 6 to 11 cm for Douglas-fir. Advance regeneration of true fir grew significantly less in the controls than in treated units ($p = 0.035$), and more under 15% retention than 40%

retention (p = 0.036; *Fig. 8a*). In Douglas-fir, no significant treatment effects were apparent (*Fig. 8b*). Maximum growth occurred in 15%A for Pacific silver fir and in 15%D for white fir (data not shown). A marginally significant effect of pattern (p = 0.073) on release index (ratio of post- to pre-harvest height growth) was negated by the significant interaction between level and pattern in true fir release index (p = 0.0058;). In this species group, 15% retention induced accelerated growth (index > 1) in dispersed treatments but decelerated growth in aggregated treatments, relative to controls and 40% retention (*Fig. 9*).

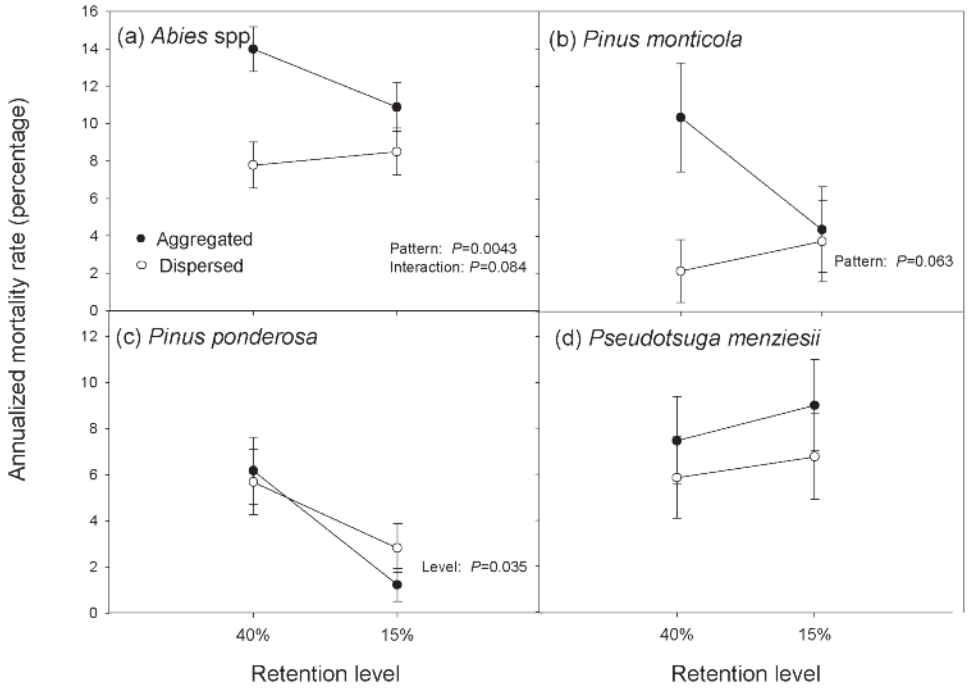

Fig. 6

Annualized mortality rate (± 1 SE) of planted seedlings by treatment and species/species group.

Jährliche Mortalitätsrate (±1 SE) der gepflanzten Jungpflanzen getrennt nach Behandlung und Baumart/Baumartengruppe.

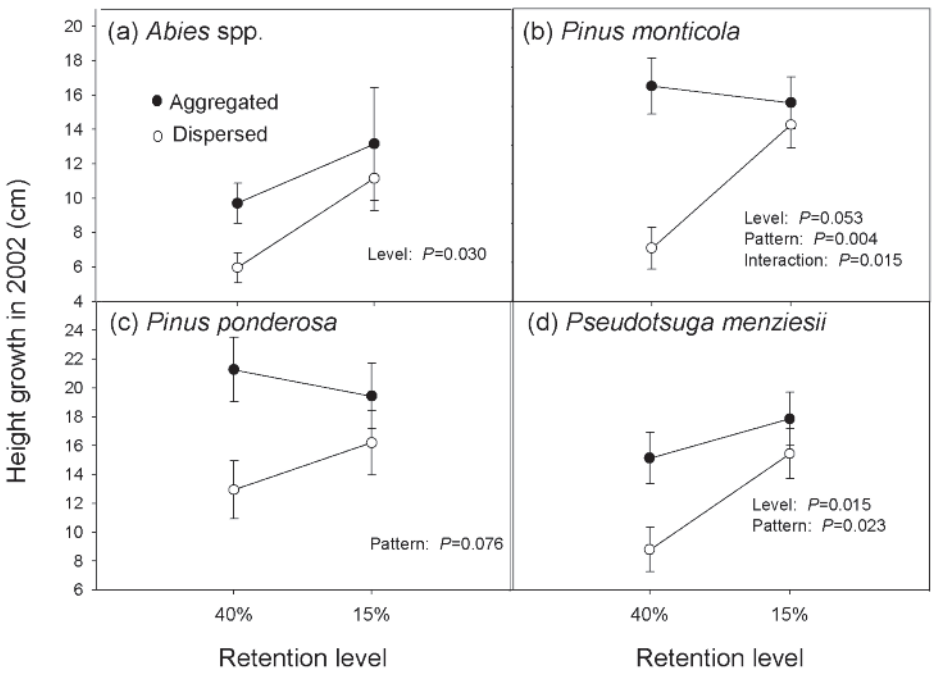

Fig. 7

Average height growth (± 1 SE) of planted seedlings in 2002 by treatment and species/species group.

Durchschnittlicher Höhenzuwachs (±1 SE) der gepflanzten Jungpflanzen im Jahr 2002 getrennt nach Behandlung und Baumart/Baumartengruppe.

Table 4

Mean density (trees ha^{-1}) of advance regeneration in all treatment units within each DEMO block, estimated from four 1x 6 m strip plots per tree plot.

Mittlere Dichte (Bäume pro ha) der Naturverjüngung in allen Behandlungseinheiten innerhalb der DEMO Blöcke, geschätzt mit Hilfe von je vier 1 x 6 m Aufnahmeflächen pro Baum-Stichprobe.

Species	*Abies amabilis*	*Abies concolor*	*Abies grandis*	*Pseudotsuga menziesii*	*Tsuga heterophylla*	*Thuja plicata*	All species
Watson Falls	0	4293	0	2078	174	0	6545
Dog Prairie	6	385	0	209	4	0	604
Butte	53	0	6	108	413	270	850
Little White Salmon	4	0	68	50	17	0	139
Paradise Hills	1074	0	1035	15	455	88	2667
Capitol	0	0	0	2	29	2	33

4. DISCUSSION

4.1 Overstory Trees

The greater overstory mortality rate for 15%D was expected given the greater exposure of the residual trees to wind and snow damage (GREEN et al., 1995). The higher mortality of Douglas-fir vs. other species is attributable to its dominant canopy position in these stands, reflecting its initial status and its selection as a priority leave species under variable retention. Mortality from wind and snow was also common on the edges bordering treatment units and on the edges of aggregates within treatment units. Wind damage on the edges of aggregates and edges of treatment units is consistent with patterns of wind damage on landscapes managed under even-age silvicultural systems (MATTHEWS, 1991).

The increase in total stem volume growth with increasing retention is well documented in numerous thinning studies (NYLAND, 2002). In general, unthinned or very lightly thinned stands maintain continuous occupancy of the site, whereas heavily thinned stands under-utilize the site temporarily, at least until the residual trees expand into the vacated growing space. The spatial distribution of residual trees was also a factor in DEMO, however. Total growth per unit initial volume was greater under dispersed treatments for at least two reasons: (1) growth efficiency of trees in lower crown classes is lower, and these trees are largely removed in dispersed retention; and (2) trees were more uniformly distributed in dispersed retention and, therefore, could more completely utilize the

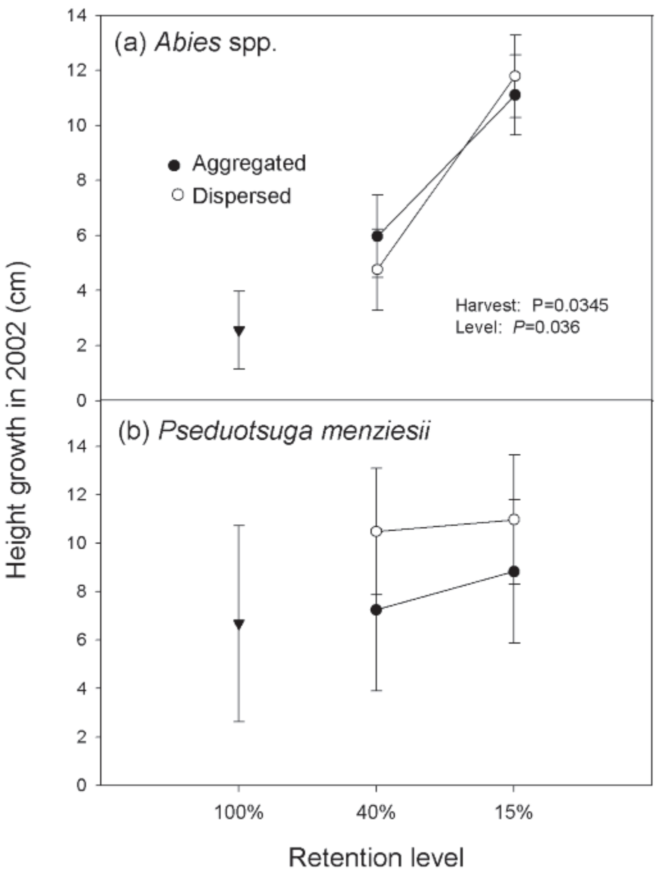

Fig. 8

Average height growth (± 1 SE) of advance regeneration in 2002 by treatment and species/species group.

Durchschnittlicher Höhenzuwachs (±1 SE) der Naturverjüngung im Jahr 2002 getrennt nach Behandlung und Baumart/Baumartengruppe.

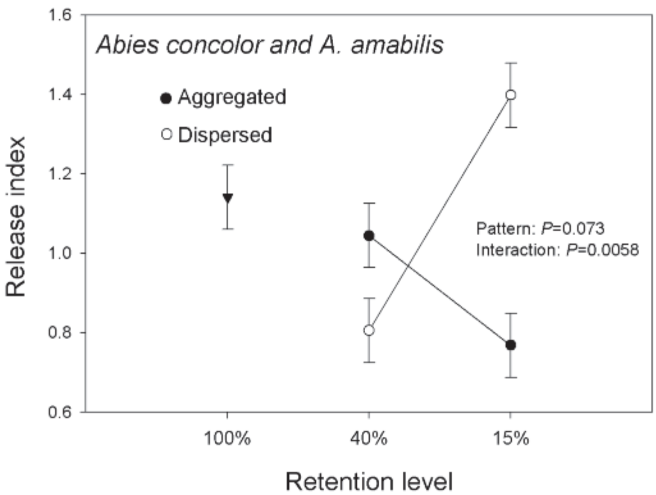

Fig. 9

Average release index (± 1 SE) by treatment and species/species group, expressed as the ratio of post- to pre-harvest height growth.

Durchschnittlicher Freistellungsindex (±1 SE) getrennt nach Behandlung und Baumart/Baumartengruppe, ausgedrückt als das Verhältnis der Höhenzuwächse vor und nach dem Eingriff.

site resources. The uniformity in tree arrangement and consequent minimal crown overlap are underscored by significantly greater canopy cover in the dispersed treatments at a given level of retention (MAGUIRE et al., in review). Some of the slower growth in aggregated treatments may also be attributable to the shock of sudden exposure, particularly for trees in lower crown classes near the exposed edge of the aggregates. Growth reduction in edge trees is analogous to thinning shock observed in some Douglas-fir stands (HARRINGTON and REUKEMA, 1983). Thinning shock could conceivably accentuate the stand density-growth correlation observed among differing levels of retention. However, the largest trees did not experience the same decline, suggesting that any growth reduction occurred only in trees of lower crown class (shorter relative height), as would be expected given their greater proportion of shade foliage (SPRUGEL et al., 1996). We expect individual-tree volume growth to accelerate during the next growth period as residual trees adjust to the new environmental conditions.

4.2 Planted Seedlings

Seedling mortality varied significantly among species, but was consistent with their ecophysiological characteristics. Mortality of shade-intolerant ponderosa pine was significantly greater under 40% retention, suggesting that light levels were too low. Mortality of western white pine was higher under aggregated retention, likely due to the relatively harsh conditions of the cut areas between aggregates. However, this effect was stronger at 40% than at 15% retention, suggesting that aspect and other factors must have contributed to mortality patterns. Regardless, the partial shade in dispersed retention units should generally benefit seedlings of this species by moderating environmental conditions while transmitting sufficient light to promote seedling survival and early growth (GRAHAM, 1990).

Height growth of all planted species in 40%D averaged only about half that in the other treatments, suggesting that additional overstory reduction may be needed to maintain understory vigor at this level of retention. In addition, because crown expansion typically reduces light levels more rapidly at higher stocking levels (CHAN et al., in press), seedling growth is likely to continue to decline in absence of further treatment. The contrast between treatment effects on mortality and those on growth has important silvicultural implications for artificial regeneration strategies in variable retention systems. For example, pattern of retention did not significantly affect ponderosa pine mortality, but growth was marginally greater under aggregated treatments, most likely due to greater light availability. In Douglas-fir, neither level nor pattern of retention affected seedling survival, but both significantly affected height growth. However, initial shade with gradual reduction in canopy cover after seedlings are established seems a reasonable strategy for establishing an understory cohort of this species. In contrast, the greater mortality of ponderosa pine under 40% retention and greater growth under aggregated retention supports previous observations that this species grows best in full sunlight (e.g., CHEN, 1997). The best retention strategy for establishment and growth of an understory cohort, therefore, varies by species and stage of seedling development. If retention of overstory trees proves successful for sustaining biodiversity, a balance must be struck between this function and ensuring adequate survival and growth of both planted and natural seedlings.

In the long run, selection of the appropriate retention level and pattern for achieving the desired stand structure must consider not only survival and early growth of understory trees, but also the vigor of both understory and overstory trees. The long-term productivity of variable-retention systems will depend strongly on the influence of residual overstory trees on understory growth and yield. Evidence to date suggests that retention of overstory trees will result in forfeiture of some growth in Douglas-fir. Several field studies and model simulations have quantified this loss in growth and/or yield, ranging from 20–30% for understory trees and slightly less for the overstory and understory together (BIRCH and JOHNSON, 1992; ACKER et al., 1998; ZENNER et al., 1998).

4.3 Advance Regeneration

In 2002, height growth of true fir advance regeneration increased as retention level declined. After four growing seasons, true fir advance regeneration may still be adjusting to the greater exposure in cut portions of aggregated treatments, although by this time seedlings have acquired four or five new age classes of needles acclimated to current light levels. The low release index (0.77) in 15%A indicated that height growth was inhibited immediately after the treatment, a conclusion corroborated by the control release index of 1.14 (*Fig. 9*). Conversely, the larger release index (1.4) in 15%D indicated a relatively rapid increase in growth during the year after harvest. By 2002, true fir advance regeneration was growing significantly better in 15% than 40% retention, and better in 40% than 100% retention (control). Despite some inhibition immediately after harvest, advance regeneration of true fir recovered quickly and accelerated growth in response to all retention levels and patterns.

By 2002, height growth of Douglas-fir advance regeneration in variable retention treatments did not differ significantly among any treatments. Height growth could not be reconstructed on any Douglas-fir seedlings back to 1997, so a release index could not be computed. The very slow growth implied by these indiscernible growth patterns and the relatively slow growth in 2002 suggest that this species may take considerably longer than true fir to fully respond to release. However, current height growth of Douglas-fir is comparable to that of true fir at retention levels of 40% and greater. Ongoing analysis of within-treatment heterogeneity in both local growing conditions and height growth will help identify the mechanisms leading to observed patterns in treatment-level averages. Height growth of advance regeneration reflects a balance between enhanced resource availability and increased stress imposed by sudden exposure of shade foliage. Increased rates of height and diameter growth are common responses of advance regeneration to various types of release treatments (HELMS and STANDIFORD, 1985; LUSSIER et al., 1992; PAQUIN and DOUCET, 1992; BOILY and DUCET, 1993; POTHIER et al., 1995). However, accurate assessment of the degree and timing of release depends on comparison to performance in both uncut controls and the open-grown condition. Two primary issues are (1) the degree and duration of any growth shock and (2) the degree and duration of suppression effects (i.e., growth that is less than expected for a tree of the same size but open-grown from germination). In black spruce (*Picea mariana* (Mill.) B. S. P.), GROOT and HÖKKÄ (2000) established an expectation based on the growth of even-aged stands, concluding that basal area growth of individual trees was less than expected for about 12 years after release. The growth shock in white fir/Pacific silver fir under variable retention apparently lasted 1 to 3 years, and perhaps longer in Douglas-fir. More detailed analysis of annual height growth is currently underway to test for the duration and degree of suppression under the various retention treatments. This test requires comparison of height growth patterns under variable retention to those from advance regeneration in the uncut controls and open-grown natural seedlings in the DEMO blocks.

4.4 Stand Dynamics

Barring catastrophic disturbance, residual overstory trees in all treatments except perhaps 15%D will persist well into the next rotation of the understory cohort. In 15%D, overstory density has continued to decline due to wind and snow damage, despite the fact that individual trees have maintained constant growth. Other causes of mortality beyond wind and snow have also contributed to losses, although most show little relation to treatments imposed in this experiment. Regardless, the erosion of overstory density will probably continue in at least some of the units and, where it does, it may frustrate efforts to achieve and maintain a two-layered structure.

In general, height growth of advance regeneration is currently slower than that of planted seedlings, although advance regeneration of white fir and Pacific silver fir is growing as well as planted stock of noble fir and Shasta red fir under 15% retention. Although these height growth responses to variable retention are probably representative of the target population, advance regeneration is patchy and infrequent in many of the DEMO units, suggesting that its future importance will be limited in some areas. In contrast, at Watson Falls and Paradise Hills, advance regeneration is relatively abundant and generally taller than planted seedlings. As a result, it will probably accelerate in growth, maintain a competitive position, and contribute significantly to understory structure and diversity. Although we did not address seedlings that established naturally after harvest in this analysis, recruitment has occurred in some locations and may contribute to understory development. In the absence of silvicultural intervention, however, we expect that in most geographic locations and treatments, the predominant component of the forest understory will derive from planted trees. Future growth of this cohort will be rapid in 40%A, 15%D, and 15%A, but its fate in 40%D remains unclear, given the continued growth of the residual overstory. Maintaining an understory that includes trees with sufficient vigor to become potential overstory trees will probably require additional overstory reduction, or starting with a lower retention level, particularly if the objective is to maintain a significant portion of Douglas-fir. However, ensuring recruitment of an understory cohort and availability of overstory replacements must be balanced against the biodiversity objectives motivating variable retention.

Understory density reduction may be a desirable component of a variable-retention system as well. As the understory cohorts continue to develop, some reduction in density may be necessary to maintain or produce stand structures that are consistent with biodiversity objectives. The understory cohort will reach crown closure in most of the tested treatments and induce predictable declines in both understory vegetation and associated wildlife populations (e.g., ALABACK, 1982). Continued treatment of both the overstory and understory will be essential components of a system designed to conserve biodiversity while providing for tree regeneration, a minimal level of understory growth and vigor, and sustained timber productivity.

5. ABSTRACT

The Demonstration of Ecosystem Management Options (DEMO) study was established in mature Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests to test the effects of varying levels and patterns of residual trees on various forest taxa and stand dynamics. Six treatments were implemented in 1997 or 1998 on 13-ha treatment units at each of six blocks in western Oregon and Washington, USA. Treatments were specified by the following levels and patterns of retained basal area: 100% retention, 75% aggregated retention, 40% dispersed retention, 40% aggregated retention, 15% dispersed retention, and 15% aggregated retention. By summer of 2003, annualized cumulative mortality of retained trees was significantly higher in 15% vs. 40% and in 15% dispersed vs. 15% aggregated retention. Retained trees failed to show any acceleration of growth in stem volume 4 or 5 yr after harvest. Four- and five-year mortality of planted seedlings was significantly greater under 40% than 15% retention for ponderosa pine (*Pinus ponderosa* Dougl. ex. Laws), but did not differ among treatments for Douglas-fir. In 2002, height growth of planted seedlings was generally least under 40% dispersed retention and was greater under aggregated than dispersed retention. In 2002, height growth of advance regeneration of white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex. Hildebr) and Pacific silver fir (*Abies amabilis* Dougl. ex Forbes) was greatest under 15% retention. Continuing wind damage in 15% dispersed retention and suppression effects of overstory trees in 40% dispersed retention may complicate attainment of vigorous two-layered stands.

6. Zusammenfassung

Titel des Beitrages: *Auswirkungen partieller Hiebseingriffe auf Altbestand und Verjüngung von Douglasienwäldern im westlichen Nordamerika.*

Der Demonstration of Ecosystem Management Options (DEMO) Feldversuch untersucht in Altbeständen der Douglasie (*Pseudotsuga menziesii* (Mirb.) Franco) Auswirkungen von Hiebmaßnahmen unterschiedlicher Eingriffsstärken mit variierender räumlicher Verteilung des verbleibenden Bestandes auf verschiedene forstliche Taxa. In den Jahren 1997 und 1998 wurden hierzu im westlichen Oregon und Washington (USA) sechs Versuchsblöcke mit jeweils sechs unterschiedlichen waldbaulichen Behandlungen eingerichtet. Die auf je 13 ha-grossen Block-Untereinheiten realisierten waldbaulichen Varianten unterscheiden sich in Bezug auf die relativ verbleibende Bestandesgrundfläche und deren Struktur wie folgt: 100% (Kontrolle), 75% konzentriert, 40% gleichmäßig verteilt, 40% konzentriert, 15% gleichmäßig verteilt und 15% konzentriert. Bis zum Sommer des Jahres 2003 war die kumulative Mortalität der verbliebenen Bäume in der 15%-Variante gleichmäßiger Verteilung signifikant höher als bei den anderen Varianten. Eine Wuchsbeschleunigung wurde in den ersten vier bzw. fünf Jahren nach den Hiebseingriffen an den verbliebenen Altbäumen nicht beobachtet. Die Mortalität gepflanzter Sämlinge der Gelbkiefer (Pinus ponderosa Dougl. ex. Laws) war in den 40%-Varianten signifikant höher als in den 15%-Varianten. Die höchste Sterblichkeitsrate gepflanzter Douglasiensämlinge fand sich in der 15%-Variante mit geklumpter Verteilung der verbliebenen Bäume. Das Höhenwachstum der gepflanzten Sämlinge war im Jahr 2002 in der 40%-Variante gleichmäßiger Verteilung am geringsten und in den 15 und 40%-Varianten mit geklumpter Verteilung am größten. Das Höhenwachstum der gesicherten Verjüngung von Douglasie, Coloradotanne (*Abies concolor* (Gord. & Glend.) Lindl. ex. Hildebr) und Purpurtanne (*Abies amabilis* Dougl. ex Forbes) war in den Varianten mit 15%-verbliebener Grundfläche im allgemeinen größer.

7. Résumé

Titre de l'article: *Conséquences d'une récolte partielle dans des peuplements de Douglas à maturité et régénération des forêts de cette essence dans l'ouest de l'Amérique du Nord.*

Le dispositif expérimental «Demonstation of Ecosystem Management Options (DEMO)» a pour but l'étude, dans des peuplements de Douglas ayant atteint l'âge d'exploitabilité, des conséquences de prélèvements d'intensités variables et des distributions diverses sur le terrain du peuplement maintenu sur pied sur la mortalité et la croissance des essences utilisées pour la régénération. Pour ce faire on a installé en 1997 et en 1998 dans l'ouest de l'Oregon et de l'Etat de Washington (U.S.A.) six blocs expérimentaux, chacun comprenant six traitements sylvicoles différents. Les sous-parcelles de ces blocs, d'une surface unitaire de 13 ha, différaient entre elles, par la surface terrière relative du peuplement maintenu sur pied et de la structure de celui-ci, comme suit: 100%

(contrôle), 75% concentrés, 40% régulièrement répartis, 40% concentrés, 15% régulièrement répartis et 15% concentrés. Jusqu'à l'été 2003 la mortalité cumulée dans le peuplement maintenu sur pied a été significativement plus élevée dans la variante 15%-distribution régulière que dans les autres variantes. Au cours des quatre ou cinq premières années après l'intervention aucune augmentation de la croissance de rieux peuplement resté sur pied n'a été observée. La mortalité des plants de *Pinus ponderosa* Dougl. Ex Laws mis en place a été plus élevée dans les variantes 40% que dans les 15%. Pour les plants de Douglas le plus fort pourcentage de mortalité a été constatée dans la variante 15%, avec peuplement laissé sur pied concentre. La croissance en hauteur des plants en 2002 a été la plus faible dans les variantes 15% et 40% avec répartition régulière et la plus forte avec les variantes 15% et 40% avec peuplement maintenu concentré. La croissance en hauteur de la régénération acquise de Douglas, *Abies concolor* (Gord. & Glend.) Lindl. Ex. Hildebr. et *Abies amabilis* Dougl. ex Forbes était en général dans les variantes avec une surface terrière restante de 15%. J. M.

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Challenges in statistical inference for large operational experiments

(With 1 Figure)

By L. M. GANIO[1),*)]

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1. INTRODUCTION

A number of large-scale silviculture experiments have been implemented in the Pacific Northwest region of North America. These experiments utilize treatment units that range from tens of hectares to more than 100 hectares to investigate effects on the scale of timber production. These operationally scaled forestry experiments are multi-disciplinary, with multiple stakeholders and multiple areas of investigation, e.g., forestry management practices, wildlife, understory vegetation, and hydrology responses. Priorities for study outcomes are based on criteria that may differ among the stakeholders and information that can be generalized broadly is important. For some disciplines, obtaining *any* information is a priority and will add substantially to existing knowledge. For land managers, information to inform management decisions is a priority. Broad scale data may be a priority in large operational experiments. Being able to meet the most objectives for the least cost may produce prioritizations. Alternatively, the strength of statistical inference, or the degree of precision, can be used to establish priorities. With potentially multiple and competing priorities, identifying high priority objectives is challenging in large-scale experiments.

Statistical inference is the process used to infer the responses of individuals in a large group based on data collected from a sample of that group. Implicitly we believe that individuals in the large group (statistical population) encompass a distribution of the response and we attempt to summarize the distribution by estimating the mean and variance of that distribution. Our ability to produce good inference is directly related to our ability to represent and estimate the variation that is present in the population. Study designs that facilitate good inference have well-defined statistical populations from which representative samples are drawn with high precision.

The paper discusses the challenge of constructing designs for operationally scaled studies where strong statistical inference is a priority. In this context, the value of information is measured by its precision, its ability to represent a larger population (scope of inference) and its unbiasedness (accuracy). In broad-scale studies with multiple researchers and areas of interest, it is unlikely that study outcomes for all researchers can achieve the same level of statistical rigor. I propose that the desire for strong statistical inference for each objective and its associated responses be prioritized among all disciplines prior to designing the study. High priority objectives can be used to design the study to produce strong statistical information and inference. During the design phase, it is crucial that these priorities are communicated and coordinated among participants so that resources can be conserved and resultant data will address inter- and multi- disciplinary questions.

In this classification scheme, *primary statistical objectives* are those objectives that drive the study design because they dictate the level of replication, the scope of inference and the spatial and temporal scales associated with treatments and measurements. *Secondary statistical objectives* are those which can be met within the structure of the primary objectives but secondary objectives have reduced precision and inferential power. In the study design process, the evaluation and refinement of design components can improve the statistical value of the ensuing information.

But as noted earlier, non-statistical criteria also generate priorities and are important. The final study design is arrived at through a process of coordinated and frank discussion that acknowledges statistical and non-statistical priorities and seeks to obtain balance among them.

2. LINKING DESIGN COMPONENTS AND THE SCOPE OF INFERENCE

The study design phase provides an opportunity to evaluate how potential, planned, or unplanned outcomes for each design component affect other components before the study is carried out. The

[1]) Department of Forest Science, Oregon State University, Corvallis, OR 97331, USA.

*) Corresponding author: LISA M. GANIO.
E-Mail: lisa.ganio@oregonstate.edu

design phase is used to think through the linkages among the design components to ensure that conclusions from the study will address the objectives (GANIO, 1998). In the design phase, ideally, primary objectives motivate the response variable, the treatment definition and the scope of inference. The treatment definition and scope of inference, in turn, define the replicate units. During the design phase, a sampling plan within replicate units is defined to ensure that data from subsamples adequately represent the large-scale units. The next step in the design process is to assess the implementation of treatments relative to the objectives. In operationally scaled studies, treatments may need to be applied in successive years. Although this may not affect long-term objectives, this may inject extra variability into short-term responses that significantly reduces the precision. If short-term objectives are primary statistical, then the treatment schedule might be altered to mitigate extra variation. Alternatively, the primary short-term objective may be modified, or reassessed as a secondary objective. The next step in the design phase is to identify the structure of the data that will be collected and develop a tentative data analysis plan to ensure that the data will address the objectives and allow desired conclusions to be drawn for the appropriate scope of inference. The design phase of a study is the time to develop a plan that is robust to planned and unplanned environmental variability and able to meet the primary and secondary objectives.

A primary objective of multi-disciplinary studies may be to synthesize conclusions across the disciplines, e.g. songbird response and understory cover. Coordination among disciplines may not occur when research teams and funding are developed within specific disciplines, so primary investigators may wish to include all disciplines in discussions during the study design process. Data collection schedules and sampling resources can be coordinated among disciplines during the design phase to ensure that responses in one discipline can be 'matched' with responses in other fields.

3. ILLUSTRATION

The initial study description for the Demonstration of Ecosystem Management study (DEMO; AUBRY et al., 1999)) is used to illustrate the potential range of objectives. I use this study plan as an example to describe hypothetically how a prioritization of objectives might have developed.

Concern over declines in populations of the northern spotted owl (*Strix occidentalis caurina*) and in its mature forest habitat in the 1980s motivated the DEMO study (AUBRY et al., 1999). A primary goal of DEMO was to provide information to develop harvest strategies that retained live trees and that could retain or accelerate the recovery of species and biological diversity found in mature Pacific Northwest forests. Overstory and understory vegetation, fungi, wildlife, hydrology, social perceptions and harvest costs were major areas of investigation. An overarching objective of DEMO was to synthesize and integrate the data from the various research disciplines to produce an overall picture of stand recovery under different treatments. The following illustrations are based on selected areas of investigation (AUBRY et al., 1999). Subsequent review and further discussion of the study design resulted in a plan that differs from the 1999 publication (PETERSON, pers. comm.)

The study was envisioned to provide applicable information for a large proportion of land in western Oregon and Washington and multiple years; i.e., the scope of inference is geographically and temporally broad. Four general research questions that focused on the effects of the green tree retention treatments were identified and were to be applied within the different areas of investigation.

The initial study design was envisioned as a randomized block design comparing six different green-tree retention patterns. All six treatments were to be implemented at each of eight geographically dispersed sites (blocks) throughout Oregon and Washington states in the northwest region of the United States. The experimental units within each block were to be approximately rectangular and 13 ha in area. Within each experimental unit, data were to be collected at each point in a systematic sampling grid with 40 m spacing (AUBRY et al., 1999). Ideally, the design structure would be developed after statistical priorities were established. In this retrospective view, I evaluate the ability of the proposed design to meet the objectives with statistical rigor and use that to identify priorities among objectives.

3.1. Identifying Primary Objectives

In the study design phase, specific responses from the major areas of investigation must be inserted into the four general research questions mentioned above to produce specific objectives. Sampling details for the specific responses in each area of investigation should be stated and then assessed to ascertain if the research objectives can be addressed for the intended broad geographic and temporal scope of inference.

As an example of an objective that achieves its intended scope of inference, consider the growth of residual trees. Growth data can be collected at each of the 60+ sampling points within each of the 13 ha units and then averaged to obtain a datum for each treatment unit. This datum represents the average response of residual trees that received that treatment. Over the entire study, many trees represent the effects of each treatment and treatments are represented (replicated) over a broad geographic extent. This scope of inference, the set of sites from which the actual used sites were chosen, is broad.

As an example of an objective that needs further clarification, consider that the study was intended to include data from wildlife species, e.g., birds, with territories that are smaller *and* larger than the planned 13 ha scale of the treatment unit (AUBRY et al., 1999). For species with territories on the order of 3–4 ha, treatment unit averages represent the average response over multiple territories (i.e., representing response of multiple animals per unit analogous to the multiple residual trees per unit). On the other hand, if a territory is larger than 13 ha on average, the data collected over the planned sampling grid within a treatment unit are subsamples of the same territory. The variation among multiple measurements within one experimental unit (variation in measurements of one territory) is a different source of variation than the variation among multiple territories. The scope of inference will be stronger for the species with smaller territories because each treatment unit will provide information for multiple territories (instead of only one). If these differences in strength of inference are discussed during the design phase then changes to the design could be made. If there is a strong need for information about the species with large territories then the size of the units might be expanded. If not, then the reduced scope might be deemed acceptable and noted in the study plan. Alternatively, species with large territories might be omitted from the study, saving resources to be used elsewhere.

A discussion of the connections between intended design, objectives and sampling plans during the design phase can identify needed changes. For example, the peer-review of the DEMO study plan identified a heavy emphasis on wildlife responses and no representation of canopy invertebrates or fungi (PETERSON, pers. comm.). The revised study plan omitted some aspects of the wildlife research to accommodate additional responses of fungi and canopy invertebrates in order to more closely meet the overarching objective of addressing biodiversity.

3.2. Potential Low Priority Objective

As an example of a potential secondary objective, snow accumulation and melt were to be measured in only one of the sites due to the difficulty of simultaneously collecting data at multiple locations (AUBRY et al., 1999). AUBRY et al. (1999) note that rain-on-snow events are among the most important factors contributing to cumulative watershed impacts, yet little is known about them. But, given the context of the study, if the objective is to understand how an event is manifested in the face of varying retention treatments, then it must be measured over replicate treatments. The ability to infer effects of particular events over the desired broad scope of inference (the blocks) is lost if only one block is measured. In AUBRY et al. (1999), hydrology objectives could be elucidated more clearly so that the distinction between understanding a particular event and understanding effects of events in the face of retention treatments is clarified. Although hydrological events are noted as important and understanding them is of high priority, the resources to provide a broad scope of inference for treatments are missing since the plan did not include measuring hydrological events over multiple treatments. This is an objective that cannot be classified as either a primary or a secondary statistical objective.

The scope of inference is defined by a study design *and* a response variable. One design may not produce the same precision (level of replication), scope of inference or accuracy for all responses in a large-scale study. A thoughtful and constructively critical discussion of the statistical priorities for objectives and responses during the design phase can clarify priorities and aid the decision-making process throughout the design of the study. *A priori* statistical power analysis can be used during the design phase to identify level of replication needed for primary objectives. Treatment units, blocks or sampling points can be added or removed to insure that high priority effects are measured with adequate precision. During the design phase, the scope of inference actually attained by the design versus the intended scope of inference can be evaluated (via discussion) to identify objectives and responses that have acceptable scopes of inference.

4. REPLICATION AND SOURCES OF VARIATION

Statistical inference relies on replicates to represent background variation within the statistical population to which inference will be made. The population must be identified so representative replicates can be selected from it. It is difficult, if not impossible to identify all sources of bias in a subjective selection process so random assignment of treatments to replicates or random selection of units to measure is often employed to control for unidentified sources of variation. But in reality, replicate sites are generally selected on the basis of availability, access, ownership, or similar features. Extensive replication is difficult for large operational experiments because few potential sites are available, and the cost of establishment, ongoing support and management can be high (MONSERUD, 2002). Operationally scaled studies are subject to constraints imposed by their size and interdisciplinary nature; the limitations this imposes on replication and statistical inference should be acknowledged during the design and reporting phase. Conclusions cannot always be extended as far as might be hoped. This does not imply that important information cannot be obtained from such studies. Carefully implemented and analyzed case studies without replication can be an important source of knowledge with implications for other settings (LIKENS et al., 1970; SCHINDLER, 1974; HURLBERT, 1984). Scientific understanding has been correctly and efficiently based on expert reasoning as well as statistical inference, but the two processes should not be confused and each should be clearly identified.

In an effort to provide larger sample sizes, researchers may advertently or inadvertently use pseudoreplication in broad-scale studies. Pseudoreplication occurs when variation *within* a single unit is used, incorrectly, to test effects of a treatment applied to the whole unit. The within-unit variation describes how one particular application of the treatment is manifest within a particular unit but does not provide inference about how a different application of the same treatment would manifest itself in a different independent unit.

Pseudoreplication is only defined in relationship to a research question. Suppose that data were collected at 25 sampling points within one treatment unit in one block. This may or may not be pseudoreplication, depending on the objective. If the objective was to understand green-tree retention treatments on residual tree growth in the Pacific Northwest, then the 25 points are pseudoreplicates because variation within one unit is being used to make inferences beyond that one unit. But suppose this one block belonged to an industrial forestry company that wanted to know how this single application affected this particular large unit. In this case, the replication is adequate to answer that question. The statistical scope of inference is narrowed to just this unit and this one treatment application. Variation within the single unit is needed to address the objective.

5. CHALLENGES AND ALTERNATIVES TO STATISTICAL HYPOTHESIS TESTING FOR LARGE-SCALE STUDIES

Statistical hypothesis testing (significance testing) is designed to test a limited number of important statistical hypotheses. When large numbers of tests are conducted on a single set of data, there are likely to be large numbers of false significant differences, i.e., Type I errors. So limiting the number of tests for any single dataset is necessary (RAMSEY and SCHAFER, 1997). Studies should be designed with reasonable ability to detect statistically significant effects if they exist, i.e. power, for the limited statistical hypothesis that they are designed to address. But because replication is often limited, the power of large-scale studies may be inadequate for some responses.

In addition, the reliance on a statistical test to infer biological significance has been widely criticized (DEMING, 1975; PRATT, 1976; COX, 1977; YOCCOZ, 1991; JOHNSON, 1999; MARINI, 1999; EBERHART, 2003). Practitioners are recognizing the value of providing estimates and confidence intervals rather than only p-values from hypothesis tests (STEIDL et al., 1997).The paradigm of statistical inference has served us well in relatively small-scale, controlled settings but it may not be relevant for landscape-level investigations for a number of reasons. Statistical inference uses the concept that "in the long run" the sample will reflect the population. But when the population is so small so large sample sizes are not possible, any particular sample may not represent the population well (HARGROVE and PICKERING, 1992). In operationally scaled studies, practical considerations such as cost and access may result in replications chosen for specific reasons, and the scope of inference may consist only of the particular large-scale units that were used. In attempting to design a good experiment, researchers may compromise broad scale objectives for the ability to replicate (COTTENIE and DE MEESTER, 2003). And arguments ensue over appropriate sources of variation to address both the statistical inference and the ecological inference (HURLBERT, 1984; OKSANEN, 2001).

But operationally scaled studies can still be valuable in the face of these inferential challenges. Some large-scale studies may address large-scale questions adequately, and others may serve as a check on existing theory (COTTENIE and DE MEESTER, 2003). Learning from studies at particular locations and comparing results from similar treatments in different locations or in different ecosystems can add to the weight-of-evidence for effects. These issues can be productively elucidated during the design of operationally scaled studies by discussing potential limitations to the scope of the interpreted study results (COTTENIE and DE MEESTER, 2003). Researchers should not extend inference to a population if pseudoreplication was used. On the other hand, inferential statistics based on pseudoreplicates may be helpful in interpreting data from the particular units in the large-scale study.

6. THE ROLE OF RANDOMIZATION

The random assignment of treatments to experimental units ensures that a treatment is neither favored nor handicapped by a known or unknown source of variation and that the measured effects we observe are reasonably believed to be true for the entire scope of inference, not just for units from which we collect data. Random assignment ensures that estimates of means and background variation are unbiased (STEEL, TORRIE and DICKEY, 1997). Through random assignment, treatment replicates are interspersed with other treatments across the geographic extent of the study. Random assignment has been an important design component of a number of operationally scaled studies (MONSERUD, 2002). But practical constraints imposed by operational scales may affect the use of random assignment. For example, treatments such as clear cutting may have to be assigned to replicate units removed from public view, or the need for specialized equipment may dictate which treatments are applied to which units. When there are few replicates, some valid random assignments may turn out to be highly structured (see HURLBERT 1984 for a good discussion). It may be tempting to actively manipulate a particular random assignment to make it appear 'more random' – perhaps to more effectively intersperse treatments. A better approach is to, *a priori*, decide to reject specifically identified random assignments as too structured (or segregated in HURLBERT's terminology) and then to redo the randomization if such an assignment occurs.

When random assignment is not used, the study becomes an 'observational study' (GANIO, 1998). Conclusions from observational studies can only identify associations between responses and treatments; they cannot infer cause and effect relationships. In reality, operationally scaled studies often fall between pure experiments (with strict random assignment) and observational studies. Even if random assignment is carefully applied, the prior site histories may differ and influence results, or other environmental effects may be interacting with treatments in a way that narrows the intended scope of inference. Statistically rigorous random assignment should not be used to dismiss the potential for real bias. Care in extending results should be taken.

7. LONG-TERM NATURE OF OPERATIONALLY SCALED STUDIES

The application of a one-time treatment may need to occur over multiple years because 1 year is not enough time to apply all treatments to all experimental units. This adds temporal variation to the data which could potentially be controlled. During the design phase, a discussion of the role of annual variation in light of the prioritized objectives can be helpful. Year-to-year (annual) variation may be controlled by applying all treatments in 1 year. When this cannot be done, temporal variation is incorporated into background variation (residual error). It can be acknowledged and accounted for by incorporating years into a blocking factor in a blocked study design, i.e., treat each block in a different year. This will remove annual or seasonal variation along with variation associated with other blocking factors. Confounding treatments with years or growing seasons should be avoided. That is, if the set of treatments cannot be applied to all replicates at the same time, care should be taken to ensure that one replicate of each treatment (replicate) is applied in any particular year. Otherwise, annual differences are confounded and confused with treatment differences.

Unacceptable stand conditions, such as high tree densities that limit growth or high densities of competitive understory vegetation, may develop over the course of the study. Alleviating the condition in an unplanned way may confound treatments and environmental conditions in ways that make assessing treatment effects difficult. Although it may not be possible to anticipate all future developments, a discussion of the potential for unacceptable stand conditions and of contingency plans to address unacceptable conditions can be helpful. The choice of action may hinge on whether the primary goal of the study is scientific inquiry or assessment of management needs.

7.1. Design Considerations for Trend Detection

Long- and short-term trends in time are of interest in large-scale studies. Statistical inference for trends may require estimating the correlation among values of the response at different times. *Figure 1* is a plot of the hypothetical responses of 2 replicate stands for treated units and control units. Questions about the difference between treated and control stands 5 years after treatment uses the data from the units only during the fifth year. These data are statistically independent from each other (experimental units are independent). But the question of whether or not the trend over 10 years differs between treated and control uses data from multiple years from each of the 4 stands. The data collected from the same stand at different times are correlated because they come from the same stand. Measurements close in time (e.g. 1 year apart) are usually more highly correlated than data farther apart in time. Ignoring this temporal correlation can produce incorrect statistical inference because estimates of variance used to construct confidence intervals or test statistical hypotheses need to account for the temporal correlation among the data values. There are a number of statistical approaches for analyzing repeated measures data (MEAD, 1988; RAMSEY and SCHAFER, 1997; VERBEKE and MOLENBERGHS, 2000).

A simple approach that avoids having to account for correlation explicitly is to phrase the question concerning the trend as a difference between responses at two points in time. For example, in *Figure 1*, a question of interest might be whether or not the difference in the response between year 10 and year 1 is different for the treated unit compared to the control. In this case, rather than using both the 1-year and 10-year responses, the difference between the 10-year and 1-year response can be constructed for each experimental unit and used as the response. Thus, there is only one response (the

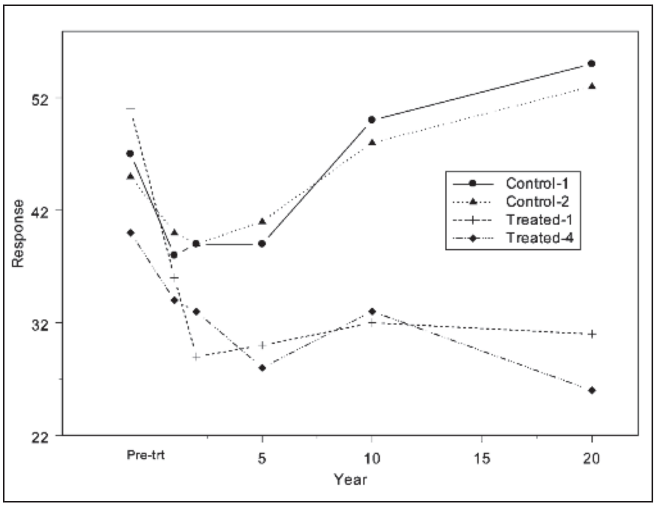

Fig. 1

Hypothetical response data from 2 treated and 2 control stands collected 1 year prior to treatment and 1, 2, 5, 10 and 20 years post treatment.

Hypothetische Reaktionen aus 2 behandelten und 2 unbehandelten Beständen, die 1 Jahr vor der Behandlung und 1, 2, 5, 10 und 20 Jahre nach der Behandlung erfasst wurden.

difference) for each experimental unit and the correlation among the time points need not be modeled.

Another approach that does not require estimating the correlation uses the slope of the time trend as the response. If the time trend is a simple linear trend, then least squares can be used to estimate the slope of the linear trend over time, separately, for each experimental unit. The estimated slopes are used as the response and ANOVA is used to test if the slopes differ between treated and control units. Again, this approach reduces the response collected at multiple times on one experimental unit to a single response of interest, i.e., the slope. Any regression software package can be used to estimate the slope for each stand. As long as only the slopes are used from the regression analysis, no assumptions such as normality or constant variance need to be checked for the regression. However, when the ANOVA analysis is carried out, assumptions such as constant variance among slope estimates must be met.

Repeated measures analysis is a more complicated approach that accounts for the correlation among the repeated measurements for each unit. Repeated measures analysis refers to a collection of statistical hypothesis tests, analogous to ANOVA tests that could be used (MEAD, 1988; RAMSEY and SCHAFER, 1997; VERBEKE and MOLENBERGHS, 2000). Repeated measures tests differ from ANOVA tests in that they use the correlation among the repeated measures to reduce the variance of the comparisons among means at different times. Not all repeated measures tests are appropriate in any one problem so descriptions of such an analysis need to identify the specific tests that were used.

During the design phase of a study that will use repeated measures analysis, it is worthwhile to consider how many of the correlations among repeated measurements will need to be estimated. Because the number of possible correlations increases as the square of the number of repeated measurements, it is possible to have more statistical parameters to estimate than data values used to estimate them. For example, a general test of the time by treatment interaction for the data in *Figure 1* would require estimating correlations among all observations for 5 different times; a total of 10 correlations. In addition there are 10 means (2 treatments at each of 5 times) and 5 variances (one for each time) giving a total of 25 statistical parameters to estimate in order to carry out the test of interaction. Because there are only 2 replications for each treatment, there are only 20 independent data points. It is not possible to estimate all 25 parameters needed for this statistical test if there are only 2 replications. In large, operationally scaled studies, it may not be possible to have enough replications to conduct particular statistical tests. Identifying and evaluating the important time-trend questions and analysis methods during the design phase is prudent to ensure that replication levels are adequate.

8. ADDITIONAL PERSPECTIVES AND CONCLUSIONS

Time series and spatial statistics are statistical methods that examine the correlation structure among different values of a single response over time or over a geographic range. In these statistical approaches, the time series or spatial surface is not replicated but many observations are collected. Thus these methods might also be applicable to large-scale studies. These techniques do not assume that the observations are independent; in fact the idea is to describe the nature of the non-independence for the particular units under study. Understanding landscape patterns might be facilitated by understanding the spatial or temporal patterns in the data (GANIO et al., 2005)

A special feature section of the journal *Ecology* suggested a wide range of statistical methods for analyzing ecological responses to large-scale disturbances (CARPENTER, 1990; JASSBY and POWELL, 1990; RECKHOW 1990; WALTERS and HOLLING, 1990) from Bayesian statistics to multivariate analysis to computer simulations. These methods are all able to help us learn about interactions among processes at multiple scales within operationally scaled studies. But these methods are only as good as the data we supply to them. If we generate data from unbiased and representative studies, then they can provide insights we might not be able to glean otherwise. The quality of the underlying data, theory and programming upon which they are based should always be made clear. Because different methods of scaling and aggregation can lead to different answers, careful consideration of these methods in simulation models is also necessary (GOTWAY and YOUNG, 2002).

Well-defined and prioritized objectives are necessary to produce an adequate study design at any scale, but it is especially critical for multi-disciplinary, operationally scaled studies. Understanding the scope of inference is necessary because it drives the choice of replicates and the space and time scales of the investigation. Coordination and communication about the study objectives and design among all disciplinary fields is needed throughout the study. In all cases, the research objectives should drive the design and not vice versa.

9. ABSTRACT

Operationally scaled silviculture experiments are typically multidisciplinary. Outcome priorities are typically based on criteria that differ among disciplines. If precise, unbiased estimates of effects and an ability to infer results to units similar to the ones in the study are important, the objectives can be prioritized into primary statistical objectives that drive the study design and secondary statistical objectives that can be met within the structure imposed by the primary objectives. The design phase of a study provides an opportunity to assess how various choices related to replication, randomization and sampling affect precision, bias and statistical inference. The use and role of statistical hypothesis testing to address objectives should also be evaluated. Throughout the study design process and the implementation of the study, coordination and communication among disciplines is important. Examples are provided.

10. Zusammenfassung

Titel des Beitrages: *Herausforderungen für die statistische Analyse und Aussage in großflächig und operational angelegten Feldexperimenten.*

Großräumige waldbauliche Feldversuche sind oft multidisziplinär angelegt weisen daher vielfach einen hierarchisch aufgebauten Zielkatalog auf. Übergeordnete primäre Fragestellungen prägen das Versuchsdesign. Die Ergebnisse sollen allgemeingültige Erkenntnisse vermitteln und auf vergleichbare Flächenareale anwendbar sein. Zusätzliche sekundäre Teilversuche sind dagegen nur in die vorgegebene Struktur integriert, ohne Auswirkungen auf diese zu haben. Die Entwurfsphase einer Großraumstudie bietet die Gelegenheit, einen derartig differenzierten Zielkatalog genau zu planen und dessen Möglichkeiten und Beschränkungen ausreichend zu analysieren. Bereits in diesem frühen Stadium des Projektes sollten wichtige Entscheidungen in der Diskussion zwischen den beteiligten Fachdisziplinen gefällt werden. Um statistisch gesicherte Ergebnisse zu erhalten und gleichzeitig begrenzte Forschungsgelder effizient einzusetzen, müssen vor der Implementierung genaue Vorstellungen über das zeitliche und räumliche Versuchsdesign sowie über die Verfahren der Datenerhebung und Datenanalyse bestehen. Qualität und Präzision gemessener Daten definieren sich durch das Ausmaß der ihnen innewohnenden natürlichen Variation. Ein durchdachtes Versuchsdesign kann trotz beschränkter finanzieller Mittel ein hohes Maß an ökologischer Variabilität gewährleisten. Ein ausreichend großer Stichproben-

umfang, die zufällige Zuordnung von Versuchsflächen (Randomisierung) und der zutreffende Zeitrahmen bieten die Möglichkeit, Zielkatalog und Versuchsdesign aufeinander abzustimmen. Insbesondere die Auswertung der Daten unterliegt statistischen Beschränkungen und Voraussetzungen. Der Wahl geeigneter, vor allem aber zulässiger, Analyseverfahren kommt daher ebenfalls große Bedeutung zu. Anhand der Demonstration of Ecosystem Management Options (DEMO) Studie, werden diese schwierigen aber wichtigen Entscheidungsprozesse und die ihnen innewohnenden Probleme und Risiken (z. B. Pseudoreplikation und Datenkorrelation) beispielhaft verdeutlicht.

11. Résumé

Titre de l'article: *Défis pour l'Interprétation statistique des expériences portant sur des surfaces importantes.*

Les dispositifs de recherches de sylviculture sur de grandes surfaces sont souvent interdisciplinaires et sont bien souvent assortis de ce fait d'un catalogue d'objectifs hiérarchiquement structuré. Les questions mises en tête détermine le design de la recherche. Les résultats doivent procurer des acquis de portée générale, utilisables pour des surfaces de terrain comparables. En revanche des recherches particulières secondaires sont simplement intégrées dans le protocole prévu, sans en modifier la structure. La phase projet d'une étude qui portera sur des surfaces importantes est l'occasion de planifier exactement le catalogue des objectifs qui doivent être différenciés et de bien analyses quelles en sont les possibilités et les limites. Dès ce stade initial du projet doivent être prises des décisions importantes, lors de discussions entre les représentants des disciplines concernées. Afin d'obtenir des résultats statistiquement valables et d'utiliser efficacement des crédits de recherches limités, il convient, avant l'implémentation, d'envisager le design temporel et spatial de l'expérience et déterminer les méthodes de collecte et d'analyse des données. La qualité et la précision des données quantitatives se définissent d'après la variabilité naturelle qui leur est propre. En dépit de moyens financiers limités, un design de recherche bien pensé permet, dans une large mesure, de parer à la variabilité écologique. Des placettes-échantillons ayant un diamètre très important, la répartition au hasard des emplacements de recherche (randomisation), des durées d'observation appropriées donnent la possibilité d'harmoniser le catalogue des objectifs et le design de la recherche. L'exploitation des données en particulier sous-entend des hypothèses et des restrictions au plan statistique. Le choix des procédés d'analyse convenables – et avant tout admis – est de ce fait de la plus haute importance. A partir des études du «Demonstration of Ecosystem Management Options» (DEMO) ces difficiles mais importants processus de décision ainsi que les problèmes et risques qui leur sont inhérents (par ex. pseudoréplication et corrélation entre données) sont éclaires à l'aide d'exemples. J. M.

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