SILVA FENNICA

Silva Fennica 45(5) review articles
www.metla.fi/silvafennica · ISSN 0037-5330
The Finnish Society of Forest Science · The Finnish Forest Research Institute

The Restorative Imperative: Challenges, Objectives and Approaches to Restoring Naturalness in Forests

Philip J. Burton and S. Ellen Macdonald

Burton, P.J. & Macdonald, S.E. 2011. The restorative imperative: assessing objectives, approaches and challenges to restoring naturalness in forests. Silva Fennica 45(5): 843–863.

Many of the world's forests are not primeval; forest restoration aims to reverse alterations caused by human use. Forest restoration (including reforestation and forest rehabilitation) is widely researched and practiced around the globe. A review of recent literature reveals some common themes concerning forest restoration motivations and methods. In some parts of the world, forest restoration aims mainly to re-establish trees required for timber or fuelwood; such work emphasizes the propagation, establishment and growth of trees, and equates with the traditional discipline of silviculture. Elsewhere, a recent focus on biocentric values adopts the goal of supporting full complements of indigenous trees and other species. Such ecosystem-based restoration approaches consider natural templates and a wide array of attributes and processes, but there remains an emphasis on trees and plant species composition. Efforts to restore natural processes such as nutrient cycling, succession, and natural disturbances seem limited, except for the use of fire, which has seen widespread adoption in some regions. The inherent challenges in restoring "naturalness" include high temporal and spatial heterogeneity in forest conditions and natural disturbances, the long history of human influence on forests in many regions of the world, and uncertainty about future climate and disturbance regimes. Although fixed templates may be inappropriate, we still have a reasonably clear idea of the incremental steps required to make forests more natural. Because most locations can support many alternative configurations of natural vegetation, the restoration of forest naturalness necessarily involves the setting of priorities and strategic directions in the context of human values and objectives, as informed by our best understanding of ecosystem structure and function now and in the future.

Keywords afforestation, disturbance regime, ecological restoration, forest rehabilitation, native species, reclamation
Addresses *Burton*, Canadian Forest Service, Natural Resources Canada, 3333 University Way, Prince George, British Columbia, Canada V2N 4Z9; *Macdonald*, Department of Renewable Resources, University of Alberta, Edmonton, Alberta, Canada
E-mail Phil.Burton@NRCan-RNCan.gc.ca
Received 29 November 2010 **Revised** 21 September 2011 **Accepted** 10 October 2011
Available at http://www.metla.fi/silvafennica/full/sf45/sf455843.pdf

1 Introduction

Only 22% of the Earth's land surface area that once had tree cover can currently be considered wild, unmanaged, and essentially natural in its ecological composition, structure and function; most of this is found in only three countries: Russia, Canada and Brazil (Bryant et al. 1997). Another 32% of former forest area (or 59% of the world's forest cover today) is in various states of disruption after logging or grazing, as managed plantations, or in small fragments. The remaining 46% of former forest land is now used for crop production and grazing, industrial activities and other infrastructure (Bryant et al. 1997). Thus, in many regions of the world, primeval forests (i.e., those with no evidence of human intervention) are a rarity or may be completely absent. Such lands lack the important functions of primeval and natural forests including serving as reservoirs of biodiversity and carbon and as living laboratories that can teach us much about ecological processes (Schnitzler and Borlea 1998, Barlow et al. 2007, Luyssaert et al. 2008).

Land owners and managers in many parts of the world are compelled to restore some aspects of forest ecosystems on land that has been deforested or degraded as a result of human activities. Driven by environmental legislation or consciousness, motivations range from improving fibre productivity to restoring biodiversity and ecosystem function. Detecting and assessing ecological degradation is typically a first step in recognizing the need for forest restoration and in prescribing methods to undertake it. Ecological degradation is often described as denoting the degree to which ecosystem composition, structure, or function has been altered from its natural or historical range of variability (Landres et al. 1999, Moore et al. 1999, Burton 2005). This begs the question of whether the "historical" period of reference is indeed representative of what is "natural" or unaffected by human actions (Swetnam et al. 1999, Higgs 2003). Nevertheless, a continuum of natural/degraded states can generally be recognized for different forest types around the world, even if different forest attributes vary in their scoring along a naturalness gradient (Brunson 2000). Setting a goal of making a forest more natural thus can result in considerable variation in objectives and approaches depending on the kind and degree of degradation, desired future land use, and location on the planet.

Ecological restoration is a broad concept that can encompass several kinds of ecological repair after some kind of damage (SERI 2004). Full ecosystem restoration is expected to return the complete set of native species (plants, animals, fungi and microbes) to a site, in the proportions and roles observed for them in undamaged ecosystems. Some restorative activities can have more specific and less ambitious objectives, including revegetation (establishment of plant cover), reforestation (accelerated establishment of trees after timber harvesting or other disturbance), afforestation (establishment of trees after a prolonged period of cover by other vegetation), reclamation (returning industrial land to a forested, agricultural, or other productive state), or rehabilitation (redirecting existing ecosystem composition or structure towards a more desired state). There is active debate and discussion around criteria and requirements for ecological restoration, such as whether degradation (and hence the need for restoration) can be a valid description of the effects of natural disturbances (e.g., a volcanic eruption or a massive insect outbreak; Dale et al. 2005, Burton 2010). Another issue is whether restoration must necessarily include a reprise of some historical condition (Higgs 2003), and whether the concept is fundamentally flawed under conditions of a changing climate (Harris et al. 2006, Millar et al. 2007). Nevertheless, there may be broad agreement on a number of factors and metrics that describe one forest condition or the state of a particular forest attribute as more natural than another. Where found, such agreement can provide direction (if not a complete template) to guide restoration activities.

The goal of this paper was to first examine the concept of restoring "naturalness" in forests, including what this might entail and the challenges associated with such endeavors. Secondly, we examined recent literature to explore the motives for and methods of forest restoration as tested or practiced around the world in recent years. For this purpose we adopted a broad definition of forest restoration including a diversity of practices which aim to return a site to a condition more closely resembling that of a natural forest.

We first analyze the concept of greater naturalness as a goal for forest restoration, recognizing many dimensions and intermediate objectives in the process. We then present a quantitative assessment of some of the recent published literature on forest restoration, with particular emphasis on the methods employed and the prevalence of published reports in different forest types and regions of the world. In so doing, some trends and recurrent issues emerge, many challenges are highlighted and it is illustrated that diverse objectives and starting conditions preclude a monolithic approach.

2 Striving for Naturalness

There is much interest in restoration efforts that can move forest ecosystems to a condition that is more natural; i.e., closer to what the condition would be in the absence of human intervention. In Europe in particular, considerable effort has gone into defining the characteristics of natural forests (e.g., Kuuluvainen 2009, Shorohova et al. 2009). The essential elements necessary for restoration approaches that strive to increase the naturalness of forests include: 1) understanding the structure and function of a natural forest suitable for the site and climate; 2) having tools and approaches that can be employed appropriately to restore these characteristics; 3) having the social and political will to seriously engage in this undertaking; and 4) having the resources and commitment for long-term post-treatment monitoring and maintenance. Do we know enough about forest structure and function to set targets for restoration? Do we have the tools to meet such targets? How much progress have we made to date? Given the complexity and spatial and temporal variability of natural forest ecosystems, are targets *per se* even appropriate?

2.1 Forest Structure and Function

Any forest (natural or degraded) can be characterized by its structure and ecosystem function and their associated temporal and spatial variability. These reflect a variety of ecological processes, which themselves demonstrate extensive variability. The structure of a forest ecosystem can be described by such aspects as: size and age structure of the trees; species diversity, composition and abundances of all organisms; spatial arrangement of individuals (in particular, the trees); physical and chemical characteristics of the forest floor and soils; and quantity (volume), abundance (density) and physical characteristics of standing and downed dead wood. These characteristics derive from population-level processes including: reproduction (birth/regeneration), dispersal, growth, death, immigration and emigration. Additionally, intra- and inter-specific interactions (including mutualisms, competition, pests, pathogens, herbivory and predation) are important drivers. The resulting forest structures and associated patterns can be described in spatial units of similarly aged or sized trees (aggregated into canopy gaps or forest stands), or as mosaics or gradients across larger forest landscapes.

The function of a forest can be described by the "ecological work" in which it is involved, including: primary production, the hydrologic cycle, nutrient cycling, carbon sequestration, decomposition, and species interactions, including trophic webs. These, in turn, are a function of aspects of the forest structure. For example, plant species composition and leaf area are major drivers of forest primary productivity. Forest ecosystem function is also heavily influenced by characteristics of the physical environment, such as landform, parent material (unconsolidated geological material underlying the soil) and climate. There are complex interactions and feedbacks between forest ecosystem structure and function. For example: nutrient cycling influences the growth and survival of trees, which in turn influences their size, spatial arrangement and litter production, subsequently affecting decomposition and, again, nutrient cycling.

Disturbance and stress affect forest ecosystem structure by killing plants and changing many other aspects of forest structure, such as the forest floor or dead wood. These factors have received particular attention from forest ecologists and managers because of their central role in the dynamic development of forest structure and function over time.

It is simple to summarize this basic forest ecology; the challenge comes in integrating this general understanding and applying it towards the goals of forest restoration (Pickett et al. 2009). Restoration of naturalness in forest ecosystems should ideally incorporate consideration of both forest structure and function and the interrelationships between them, and attempt to restore natural processes (e.g., Lenz and Haber 1992, Allen et al. 2002, Gomez-Aparicio 2009).

2.2 The Challenges of Heterogeneity and Landscape Context

As discussed by Peterken (1996) and others (e.g., Angermeier 2000, Brunson 2000, Machado 2004), naturalness is a continuous variable and natural forest landscapes include a great variety of forest types and conditions. Truly primeval or natural forests can include, for example, both young (early post-disturbance) and old forests as well as forests of both high and low productivity. Sincere efforts at forest restoration should embrace this variability. For example, it has been emphasized that incorporation of temporal and spatial variation is important when restoring habitat for wildlife (George and Zack 2001). Spatial and temporal heterogeneity, however, present a major challenge because of difficulties with identifying restoration targets and measures of success, and also because of the need to ensure that restored forests can vary naturally into the future.

Forest structure and function change over time as a result of the interplay between population processes, disturbance or stress and other external factors (Glenn-Lewin et al. 1992). Such patterns of change occur at a variety of spatial scales from patch or gap dynamics to stand dynamics and landscape change (Pickett et al. 1987). Successional dynamics are complex and much work has gone into documenting patterns, examining underlying processes, and developing models to aid in understanding vegetation change (e.g., Pickett et al. 1987, Glenn-Lewin et al. 1992, Taylor et al. 2009). While forest successional development is often characterized by gradual composition change over time following disturbance, this is not always the case. There are examples showing that a forest ecosystem could exist in a given forested state for millennia and then, as a result of natural disturbance (Asselin and Payette 2005b) or a change in climate (Berg et al. 2009), shift rapidly to a dramatically different ecosystem type. Further, species distributions are dynamic and at northern latitudes some may still be demonstrating post-glacial migrations (e.g., Johnstone and Chapin 2003). The dynamic and unpredictable nature of forest composition, structure and function pose a challenge for establishment of restoration targets.

Even with good information on the range of forest conditions which exist on the landscape and how they have changed over time, we often don't know whether a given condition should be considered natural (Swetnam et al. 1999, Jackson and Hobbs 2009). Characterization of the primeval forest condition is difficult in many regions of the world because of long histories of human use and management (Hobbs et al. 2009) combined with natural or human-caused climate change (Shuman et al. 2009). Untangling these effects can be challenging. For example, careful assessment of a variety of historical data sources throws into question the concept that fire suppression and grazing are the root cause of tree and shrub encroachment into rangelands and increases in forest tree density in the southwestern United States (Swetnam et al. 1999); other possible drivers of these vegetation changes include post-glacial migration, climate variability, and recovery from prior natural or anthropogenic disturbance. Gimmi et al. (2010) showed that a transition from pine-dominated to deciduous-dominated forest in the Swiss Rhone Valley could be explained by the combined influence of pine mortality due to drought stress along with increased deciduous tree regeneration, which resulted following abandonment of grazing and litter collection practices.

The stochastic nature of natural disturbances is well known. For example, the annual area burned by lightning-caused wildfires in the province of Alberta, Canada, between 1990 and 2008 has an extremely skewed distribution, varying from 322 ha to over 650,000 ha (Fig. 1A). Similarly, the forest area within the province of Quebec, Canada, that experienced moderate to severe insect defoliation between 1990 and 2009 varied annually from 1361 ha to over 1.36 million ha (Fig. 1B). Comparable variation has been documented for European forests, where annual area burned from 1960 to 2000 varied about five-fold

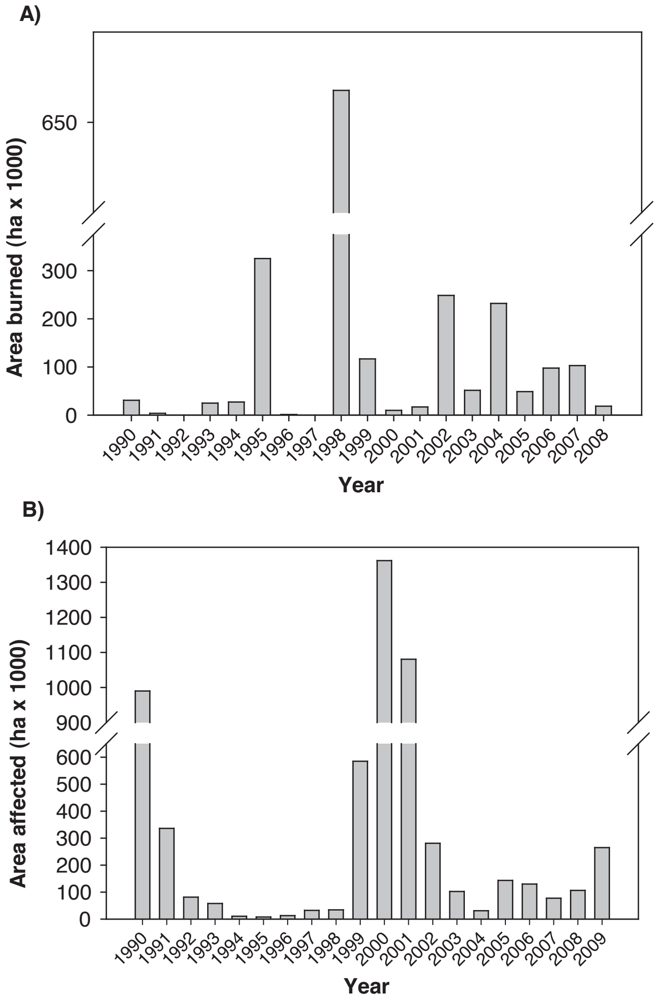

Fig. 1. Annual area affected by: A) lightning caused forest fire in Alberta, Canada; and B) moderate to severe insect defoliation in Quebec, Canada (source: Canada's National Forestry Database, http://nfdp.ccfm.org).

while the annual volume of wood damaged by storms varied by well over twenty-fold (Schelhaas et al. 2003). Such extensive inter-annual variation in disturbance makes it essentially impossible to define an equilibrium landscape-scale age structure that represents a "natural" condition (Armstrong 1999). Natural disturbances are also spatially heterogeneous at various scales and this has important implications for forest regeneration and successional development following fire (Turner et al. 1997, Johnstone and Chapin 2006, Greene et al. 2007, Hayes and Robeson 2009), landslides (Restrepo et al. 2009) and windthrow (Ulanova 2000, Canham et al. 2001). Given that the composition and structure of a given forest landscape is a function of such stochastic disturbance effects, along with complex post-disturbance successional development, it is extremely difficult to recognize any given forest condition as natural.

Even where the natural forest composition, structure and disturbance regime is not well understood, we can often recognize the current state as one that is likely substantially different than what it would be in the absence of human intervention. In many regions, long histories of human land use have affected forest composition (Peterken 1996, Björse and Bradshaw 1998, Svenning et al. 2009) to the point where the natural forest composition is simply not known (Bradshaw and Holmqvist 1999). Likewise, it is often a challenge to characterize the historical natural disturbance regime (Conedera et al. 2009, Niklasson et al. 2010, Zielonka et al. 2010). Additional complexity comes from a lack of understanding about potentially important interactions among multiple disturbances (Paine et al. 1998).

Another challenge for restoration of naturalness in forests comes from the influence of the surrounding landscape on the potential for successful restoration. It will be very difficult to restore natural ecological processes such as dispersal and immigration if the area targeted for restoration is embedded within a matrix where cover and composition have been dramatically transformed by humans (Jacquemyn et al. 2003, Herault et al. 2005). Restoration efforts in such situations may be further hampered by the loss of key species (Ellison et al. 2005) or by external influences such as invasive species (Mooney and Hobbs 2000). Other external factors, such as atmospheric pollution, can also make it difficult to restore natural species composition (Lenz and Haber 1992).

2.3 Aiming at a Moving Target

Changes in forest composition over long time periods have been associated both with direct effects of climate variation and with climate-induced changes in disturbance regime (Carcaillet et al. 2001). Forest composition can, in turn, influence flammability, thus mediating changes in fire regime associated with climate change (Brubaker et al. 2009). Over the past few centuries and millenia, the frequency of natural disturbances such as fire have changed dramatically; this has often been attributed to changes in climate (Johnson 1992, Bergeron and Archambault 1993, Carcaillet et al. 2001, Girardin et al. 2009). Such variation in natural disturbance regime is often associated with concomitant variation in forest composition (Asselin and Payette 2005a, Jasinski and Payette 2005, Ali et al. 2008), an important consideration in defining and restoring naturalness. In planning forest restoration efforts it is critical to consider the future climatic regimes within which these dynamic interactions between climate, disturbance and vegetation change will play out. Even if the historical "natural" forest composition or disturbance regime is known, these might not be compatible with current or future climatic conditions (Bradshaw et al. 2005).

The influence of future climates on vegetation (Girardin et al. 2008, Morin et al. 2008, Tang and Bartlein 2008, Morin and Thuiller 2009), species interactions (Gilman et al. 2010) and natural disturbance regimes (Parisien and Moritz 2009, Girardin et al. 2009) are likely to be heterogeneous and unpredictable. Thus, past experience may not provide the information we need to tackle restoration in the face of such future uncertainty. Interactions between climate, disturbance, and vegetation change will continue in the future, under climate conditions for which we may have no analogue and disturbance regimes over which we have little control (Flannigan et al. 2005, Schumacher and Bugmann 2006). The result could be dramatic shifts in the "natural" forest landscape (Johnstone et al. 2010). The emergence of novel ecosystems is inevitable (Hobbs et al. 2009).

3 Review of Recent Research in Forest Restoration

3.1 Evaluating Published Descriptions of Forest Restoration Research

Despite some of the challenges noted above, forest restoration activities seem to be increasingly popular. We were interested in documenting recent trends in forest restoration, and in examining the alignment of objectives, methods, and recognized limitations. To this end, we undertook a comprehensive examination of the published scientific literature on forest restoration using three different approaches:

1) Firstly, the "advanced search" options of Google™ Scholar® were used to document the degree to which forest restoration has been reported in the

research literature in the decades since 1960 (recognizing that the database is likely both sparser and less complete for the more distant past). For those searches (conducted 24 July, 2010 from Prince George, Canada), a variety of keyword combinations were specified for different time periods as follows: (reforest* OR afforest*), ("forest rehab*" OR "woodland rehab*"), and ("forest restor*" OR "woodland restor*") for all years through 2009, subsequent to and including 1960, 1970, 1980, 1990 and 2000; decadal summaries were determined by subtraction.

2) Secondly, articles published from 2000 to 2009 in three relevant journals were then searched for more details regarding restoration objectives and approaches. The journals searched were *Ecological Restoration* (an official publication of the Society for Ecological Restoration International), *Conservation Biology* (an official publication of the Society for Conservation Biology), and *Forest Ecology and Management* (an international journal with no affiliation to a scientific, scholarly or professional society). Many other journals and trade publications also report aspects of forest restoration, and it could be argued that the ones selected are biased to research more than operational practices. It was felt, nevertheless, that these three journals adequately represent the specialized restoration community, the general biological conservation community, and the forestry community, respectively. Articles dealing with some aspect of forest restoration were tallied for each of 20 issues of these three journals (alternating between the beginning and end of the decade until 20 issues were assessed; i.e., using data from the years 2000, 2001, 2002, 2008 and 2009) and reported as a percentage of all articles in each issue.

3) Finally, we undertook a more detailed exploration of articles in *Restoration Ecology*, as this journal is the most prolific publisher of forest restoration articles. Data from all 43 issues published between 2000 and 2009 were gathered; 279 articles on forest restoration (broadly defined, as described above) were browsed to discern the purpose of the study or the reported restoration activities; and we documented the location, treatments undertaken, attributes measured, and the period of post-reclamation study. A total of 11 motives and 25 approaches were scored as being present in (1) or absent from (0) each article, and were then cross-tabulated. When new objectives or methods were encountered, the previously viewed articles were re-evaluated to make sure that these features were searched for in them as well. To evaluate international trends, results were tested for relationships to national statistics on land area, human population and forest area as compiled by the Food and Agriculture Organization (FAO) of the United Nations (FAO 2009). Results were summarized in terms of time periods, forest types, and the prevalence of different restoration objectives and methods. Contingency table analysis was used to test for significant associations between objectives and methods (TABLES statement in FREQ procedure of SAS v9.2; SAS Institute 2010). We further tested for correlations between the frequency of forest restoration papers in different countries and each nation's population density, gross domestic product, proportion of forest cover, and forest cover per capita (using the CORR procedure of SAS v9.2; SAS Institute 2010). A copy of the database describing the 279 articles examined is available from the first author.

3.2 Trends Over Recent Decades

It is evident that forest restoration activities have not always been referred to under that rubric. Based on the Google Scholar search, the terms "restoration" and "rehabilitation" as applied in an ecological context were practically unheard of in the 1960s and 1970s (Fig. 2). Nevertheless, reforestation (and to a lesser extent afforestation) was commonly practiced, studied and reported on during that time period. There has been a steady increase in the number of publications referring to forest and woodland rehabilitation or restoration since the 1970s, with the term or practice of "rehabilitation" less preferred in comparison to the more general "restoration." However, these terms and practices have not replaced those of reforestation and afforestation, which continue to grow as the most important subjects of study in this constellation of terms. It is also likely that the use of these terms, and the subtle distinctions among them, shift over time and differ among cultures and regions, even when translated accurately into English.

Of the 279 *Restoration Ecology* articles evaluated in detail, 199 (71%) of them assessed or

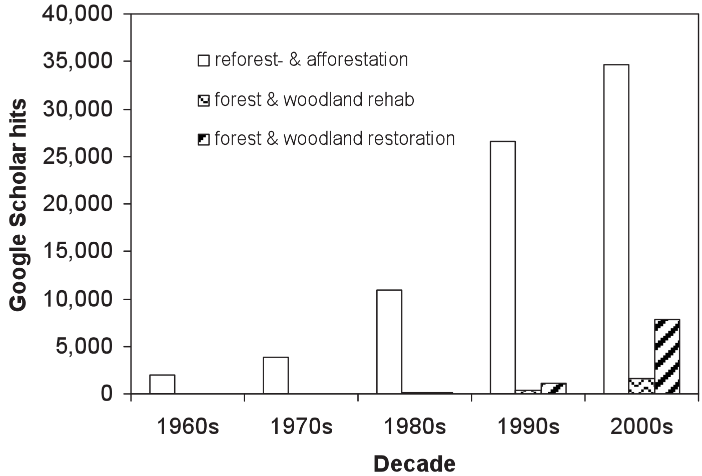

Fig. 2. Summary of published articles listed in Google^{TM} Scholar® tallied by the search terms (reforest* OR afforest*), ("forest rehab*" OR "woodland rehab*"), and ("forest restor*" OR "woodland restor*") in specified time periods.

asserted the effectiveness of restoration treatments in meeting project objectives. But of those 199, only 5 (2.5%) showed no significant difference among treatments or between treated and untreated areas. This suggests a strong publication bias, common in many scientific disciplines, in which non-significant treatment effects go unreported (Lortie et al. 2007). The modal period of time between restoration treatments and their (longest) reported evaluation is only 2 years, but many studies have included retrospective analysis of older restoration programs, so the median post-evaluation time reported was 4 years (Fig. 3).

3.3 Trends Among Journals and Disciplines

The journal *Restoration Ecology* led the way in reporting on forest restoration topics. In the 20-issue period of comparison, an average of 36±5% (mean ± S.E.) of the articles in each issue of that journal dealt with forest restoration. In contrast, *Conservation Biology* averaged only 5±1% articles per issue dealing with forest restoration over a similar 20-issue period of comparison. *Forest Ecology and Management* was intermediate, averaging 18±4% of articles per issue dealing with forest restoration in the broadest sense, with considerable emphasis on regeneration silviculture and wildlife habitat management.

These trends are not surprising: approximately 42% of the world's land area is characterized as being within forested biomes (Jenkins and Joppa 2009), so it is appropriate for a similar proportion of space in *Restoration Ecology* to be devoted to forest-related topics. While conservation biologists recognize the importance of ecological restoration, the priority of that profession and its journals is on the protection of natural biodiversity (genotypes, species, ecosystems, landscapes), with restoration generally considered a second-choice (though often necessary) alternative to conservation (Primack 2006). Forestry research and forest management practices have a long history of addressing forest regeneration – indeed, it could be said that modern forestry began in the 18th and 19th centuries in response to the need to restore the forests (or at least their wood-producing and wildlife-supporting functions) of central Europe (Floyd 2002, Batho and Garcia 2006, Fischer and Fischer 2006). Thus it is understandable that a good proportion of space in a mainstream forest science journal such as *Forest Ecology and Management* would be

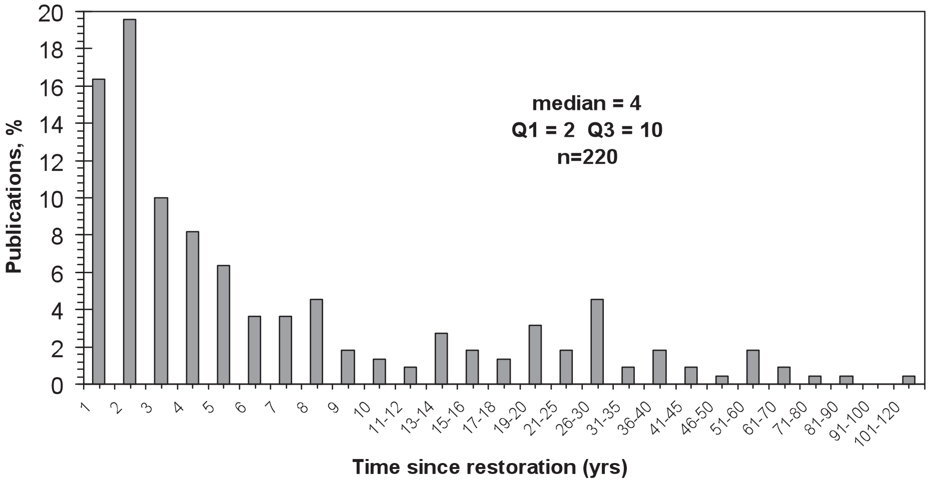

Fig. 3. Frequency distribution of the period of time between the application of restoration treatments (or the cessation of degrading activities in the absence of active management) and the most recent post-restoration evaluation for forest restoration articles published in Restoration Ecology between 2000 and 2009. Note uneven x-axis intervals.

devoted to topics of reforestation, forest renewal, and (increasingly) the restoration of habitat and ecosystem services.

3.4 Geographic Trends in Forest Restoration Research

Most of the tallied papers (53% of n = 279) on forest restoration were based on work conducted in North America, especially the U.S.A. This likely reflects, in part, the fact that *Restoration Ecology* is published in that country and is published only in English. Results may also reflect cultural differences, with many restoration projects in the developing world unlikely to have been the subject of research and publication. For example, widespread international support for the Forest Landscape Restoration initiative (IUCN 2002, Maginnis and Jackson 2002), and its implementation for both ecological and socio-economic benefits, are largely unreported in the scholarly literature. There were no significant trends in the representation of countries (n = 34) according to their percentage of remaining forest ($r = -0.06$, $p = 0.758$), nor the area of forest per capita ($r = 0.16$, $p = 0.375$). Neither was there a significant correlation between the number of publications from each country and that nation's population density ($r = -0.19$, $p = 0.288$). On the other hand, there was a significant positive correlation with a nation's per capita gross domestic product ($r = 0.42$, $p = 0.014$). This suggests that it is not the rarity of forests per se that results in the implementation (or at least the consideration and study) of forest restoration, so much as the affluence of the society and perhaps its freedom from more immediate issues of food production and overcrowding.

Related trends are observed in the representation of different forest types in which restoration has been studied and attempted. Temperate broadleaf and floodplain forests make up the largest block (37%) of recent forest restoration publications, followed by tropical forests (including mangroves) collectively (20%), temperate and montane conifer forests (19%, largely pine woodlands), and then by Mediterranean forests and woodlands (12%; Fig. 4). Although again potentially influenced by the socio-economic situation and culture of the nations sponsoring such work, there appears to be a widespread commitment to restore forest cover on temperate and tropical lowlands that were previously

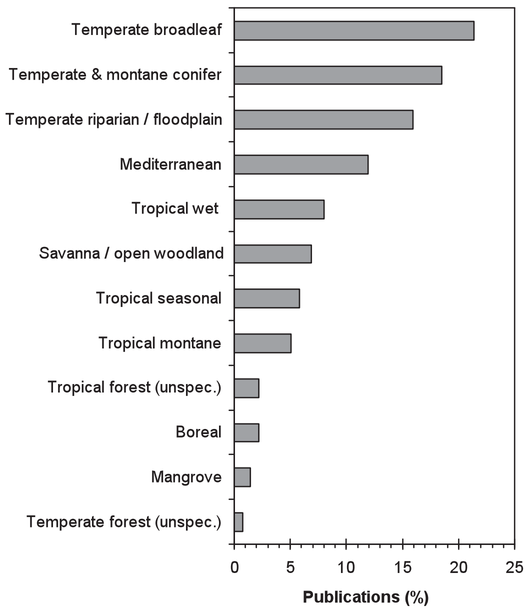

Fig. 4. Representation of different forest types in restoration publications (n = 276) assessed in the journal Restoration Ecology for the period 2000 to 2009.

used for crop production or livestock grazing. Perhaps because of their widespread persistence as wild forests, low human population levels, or little public demand, there is little (2%) mention of boreal or subarctic forest restoration in this sample, although the journal *Silva Fennica* did publish a special issue on the topic of boreal forest disturbance with a particular focus on restoration (Kuuluvainen 2002).

3.5 Motives for Forest Restoration

The motives for forest restoration are not always specified in published case studies and experimental projects, presumably because forest restoration is always perceived as a "good thing to do". Where restoration goals are stated, they are often vague and very general, such as to "promote diversity" (46% of papers). Reclamation after mining or other industrial activities has also dominated much research and analysis, and was responsible for 25% of the papers considered. General reforestation, afforestation, and the successful establishment of trees for wood supply follows (22%); providing habitat for wildlife or rare species was equally represented (22% of papers). Post-agricultural restoration in which grazing lands or cultivated fields are being returned to forest cover also figured prominently (21%). Stanturf and Madsen (2002) argue that the core land use context for most forest restoration work centers on this dynamic between deforestation (as a result of agriculture and urban or industrial uses) followed by afforestation and reclamation. Other less prevalent goals include the improvement of forest health and the reduction of fire risk, particularly in fire-maintained forest types (14% of papers), the protection of aquatic or marine resources (10%), general erosion control (6%), restoration of culturally important forest types (3%), and repair of damage caused by trampling or recreational use (1%). Motives are often multi-faceted, so these proportions sum to more than 100%.

3.6 Approaches to the Study and Improvement of Forest Restoration

Forest restoration in much of the world focuses primarily on tree species (a practice or approach in 73% of papers assessed; see Table 1). This suggests that forest restoration is often not very different, in practice, from basic silviculture as conducted as part of sustainable forest management, where the re-establishment of a new cohort of trees constitutes the principal investment in assuring forest renewal after timber harvesting (Smith 1986, Burton 1998, Lieffers et al. 2003). The next largest approach (in 51% of papers) consists of the establishment or evaluation of plant species other than trees, usually in addition to working with trees. This suggests that almost half of restoration researchers and practitioners recognize the ecological community context of forest restoration. The comparison and enhancement of propagation methods (seed introduction, planting) figures prominently (37%), followed by the evaluation or enhancement of soil properties (including the use of fertilizer, lime, etc.; 33%). Next important was the selective removal, control or thinning of trees and brush, employed in 29% of the papers; a number of those and related

Table 1. Cross-tabulation of forest restoration approaches and motivations, as described in *Restoration Ecology* articles from 2000 to 2009. Cell contents are number of articles (of n=279) in which a given approach was employed in addressing a given motivation. **Bold** values denote a significant association between approach and motivation, either postive (+) or negative (–). Rows (top to bottom) and columns (left to right) are listed in decreasing order of total encounters.

Approaches, methods employed, factors assessed	Motivation for restoration											
	Promote forest regen-eration, diversity	Reclama-tion after mining, urban, or industrial activity	General reforesta-tion, affor-estation	Old fields, post-agri-cultural reclama-tion	Habitat or connectiv-ity for wildlife	Improve forest health, reduce fire risk	Protect aquatic resources, habitats	Protect or establish rare spe-cies	Erosion control	Restore culturally important forest types	Repair damage from trampling, recreation	Total [a)]
Tree species	95	52	**53(+)**	**49(+)**	22	24	22	13	15	5	**1(–)**	202
Non-tree plant species	**81(+)**	40	22	29	**10(–)**	16	10	10	10	3	2	141
Propagation (including seeding, planting)	**39(–)**	33	**34(+)**	27	**7(–)**	**5(–)**	11	7	8	3	2	104
Soil properties (amelioration, fertilization, mycorrhizae)	**28(–)**	**41(+)**	21	18	**4(–)**	**5(–)**	**4(–)**	2	8	3	**4(+)**	91
Thinning / brushing	**49(–)**	**4(–)**	13	18	16	**24(+)**	7	3	2	3	0	82
Template defined or sampled	37	19	15	14	16	13	9	5	7	2	2	81
Spontaneous recovery or succession assessed	29	20	13	**21(–)**	**4(–)**	**2(–)**	4	4	3	1	1	58
Landscape analysis	29	10	12	14	11	6	**10(–)**	3	6	2	0	54
Fire	**31(–)**	**7(–)**	**5(–)**	**3(–)**	10	**24(+)**	3	4	2	2	0	53
Microsites / horizontal structure or pattern	23	8	12	14	10	4	6	**7(–)**	2	1	1	47
Disturbance regime	25	6	**2(–)**	5	10	**16(–)**	6	4	3	2	1	45
Animal populations, communities	15	9	8	**3(–)**	**25(+)**	7	3	4	3	0	0	42
Effects or removal of exotic species	**27(–)**	7	4	7	6	3	6	2	1	2	0	38
Protective structures, barriers	14	8	11	9	4	**0(–)**	6	2	2	1	2	36
Tree size-class distribution / vertical structure	16	4	4	6	7	**11(–)**	3	2	3	2	0	33
Hydrology, water relations or irrigation	13	7	8	5	4	1	**10(–)**	0	2	2	1	31
Nurse plants, or successional plantings/planning	**14(–)**	4	**17(–)**	**12(–)**	3	**0(–)**	2	2	3	1	1	29
Herbivory	17	**2(–)**	8	**11(–)**	1	**0(–)**	5	1	2	1	0	29
Mulch, organic matter	8	10	**10(–)**	4	1	2	1	2	3	0	2	26
Ecosystem processes (N cycling, C sequestration, etc.)	12	4	8	6	7	4	3	0	**4(–)**	0	0	25
Seed bank	11	**14(–)**	3	3	2	**0(–)**	1	0	1	0	0	22
Deadwood / coarse woody debris	10	1	3	3	5	3	**5(–)**	1	1	0	0	18
Cost efficiency	5	2	3	1	4	2	3	0	1	0	0	12
Rare species reintroduction	3	0	0	0	2	0	0	**9(+)**	0	0	0	9
Total [a)]	129	69	62	58	43	39	28	19	17	8	4	279

[a)] Rows and columns do not always sum to 279, as multiple approaches were usually employed in addressing a given motivation, and multiple motivations were sometimes pursued in a given operation/study.

papers (14% of the total) specifically addressed exotic species and their effects. Considerable effort (addressed in 29% of the papers) has also been applied in determining the appropriate template or "naturalness target" for restoration, specifically addressing one of the major challenges discussed in section 2. Spontaneous recovery and natural succession was studied in 21% of the cases, followed by landscape-level analysis and spatial considerations (19%), evaluations of fire effects (19%) or those of disturbance regimes more generally (16%). The evaluation or restoration of microsites and other aspects of spatial pattern made up 17% of the papers reviewed. Animal populations were studied in 15% of the cases. The evaluation and restoration of tree cohort proportions and canopy structure played a role in 12% of the papers. Nurse plants or successional planting was employed in 11%. Physical structures or barriers (typically for tree protection, though sometimes for soil stabilization) were employed in 13% of cases, and the need to control herbivory was recognized in 10% of papers. Hydrology, water relations, or the use of irrigation was considered in 11% of papers. A number of other seemingly important factors and methods did not feature prominently over the last decade in the journal *Restoration Ecology*; the evaluation or restoration of ecosystem processes (such as pollination, nitrogen fixation, nutrient cycling, carbon sequestration), the evaluation or addition of dead wood (standing snags, fallen logs), the use of seed banks, mulch or organic matter, and the introduction of rare species were each featured in less than 10% of the journal articles (see Table 1). Considering that most restoration activities involve active management and investments of time and resources, surprisingly few (4%) articles discussed or compared costs.

A number of restoration methods are recurrently and significantly associated with particular restoration objectives (Table 1). Approaches that focus on trees and the evaluation or introduction of various tree species figure prominently, especially where the goal is reforestation/afforestation ($\chi^2=6.83$, $p=0.009$), and the restoration of agricultural land ($\chi^2=5.35$, $p=0.021$). Conversely, approaches that focus on plant species other than trees are typically associated with an objective of diversifying forests or promoting forest regeneration ($\chi^2=14.41$, $p<0.001$). Plant propagation techniques, often including comparisons of planted nursery stock, direct seeding, or the use of cuttings, are significantly associated with reforestation ($\chi^2=10.52$, $p=0.001$). Thinning of the tree layer or the brushing and weeding of less desired species is likewise associated with a suite of forest health improvement and fuel reduction treatments ($\chi^2=22.58$, $p<0.001$). Various combinations of thinning and prescribed fire are the treatment of choice for fire-dependent ecosystems, especially pine woodlands found in sub-tropical (e.g., *Pinus palustris*), temperate (e.g., *P. ponderosa*) and even boreal (*P. sylvestris*) climates. Restoration approaches involving analysis of soil properties and soil amelioration are often undertaken with an objective of repairing recreation damage ($\chi^2=8.384$, $p=0.004$) and are the most important aspects of mined land reclamation ($\chi^2=29.97$, $p<0.001$). Although not used widely for reclamation (a negative association, $\chi^2=19.42$, $p<0.001$), seed banks played a big role in reclamation after bauxite mining in Western Australia, in which more than 6400 ha of jarrah forest (dominated by *Eucalyptus marginata*) has been successfully restored with more than 130 native species over a period of 11 years (Grant 2006, Koch and Hobbs 2007). Almost by definition, work with animals figures prominently where the provision of wildlife habitat is a stated goal ($\chi^2=73.80$, $p<0.001$), as is the introduction of rare species where the recovery of threatened species is intended ($\chi^2=127.26$, $p<0.001$). A large number of techniques and considerations are also negatively associated with particular restoration objectives (Table 1). For example, soil factors are under-represented in restoration approaches with an objective of forest diversification ($\chi^2=13.00$, $p<0.001$), wildlife habitat ($\chi^2=12.57$, $p<0.001$), improving forest health ($\chi^2=8.08$, $p=0.005$), and protecting aquatic resources ($\chi^2=4.76$, $p=0.029$). Similarly, fire is rarely used to promote forest regeneration and diversification ($\chi^2=3.95$, $p=0.047$), mine reclamation ($\chi^2=4.67$, $p=0.031$), reforestation ($\chi^2=6.19$, $p=0.013$), or old-field recovery ($\chi^2=9.09$, $p=0.003$).

4 Implications

4.1 Approaches to Forest Restoration

Even without complete understanding or identifiable targets, people around the world are undertaking forest restoration. Reflecting early needs to produce more wood for fuel and building materials, and the simple fact that forests are defined by the dominance of trees, there has long been an understandable emphasis on the establishment and promotion of tree cover. Recent years have seen a more sophisticated understanding of the more subtle dimensions of forest ecosystem integrity. This understanding, in combination with a diversity of climates, pre-disturbance forest types, policy-driven management objectives, and conditions under which restoration is undertaken has resulted in the employment of a wide variety of methods and approaches.

Our analyses of the literature (presented in section 3) illustrate that forest restoration efforts have focused heavily on re-establishment of the tree component of forest structure with a particular emphasis on composition, density, size structure, and to some degree spatial distribution. Restoration of plant species other than trees has also received a fair amount of attention, particularly with the objective of promoting forest regeneration and diversity. Given the strong influence of trees in particular and plants in general on forest ecosystem function, it seems likely that re-establishment of site-appropriate vegetation will go a long way towards restoration of functions such as primary productivity, the hydrologic cycle, litterfall, decomposition and nutrient cycling (Grime 2002). There has been little in the way of specific efforts to restore these ecosystem functions but a number of studies have examined recovery of hydrology, nutrient cycling and carbon sequestration following restoration (Table 1). The soil component, particularly organic matter and nutrients, is the other aspect of forest structure that has received quite a bit of attention in forest restoration studies (although often simply in the form of fertilization) followed by investigations of thinning, brushing and weeding (Table 1). Restoring composition and diversity of species other than plants remains a challenge, and at least in the literature we reviewed, has not been well explored except in the case of species of particular interest (e.g., reintroducing rare species, removal of exotic species).

Restoration of the processes underlying ecosystem structure and function is much more challenging. The initial stages of regeneration are addressed through planting or seeding, studies of seed banks, and microsite creation (Table 1). Forest maintenance and diversification may require further interventions (e.g., successional plantings) or will depend on the development of natural regeneration processes in the restored ecosystem, which could be partly facilitated (e.g., through the establishment of nurse plants). Processes of tree growth can be encouraged or allowed to proceed under competitive pressure in many ways, especially through the control of stocking and spacing (Smith 1986, Lieffers et al. 2003). Other aspects of population demography in plants and animals, such as death, immigration and emigration, are not very easy to manage. Restoration of more complex processes such as species interactions is attempted intermittently, but is constrained by pre-conceived notions of good forest management that have evolved as a result of emphasis on timber production. Mutualisms such as mycorrhizal relationships thus are being explored (e.g., Kernaghan et al. 2002, Allen et al. 2005), but pests, pathogens, herbivory, and predation are still generally considered undesirable or are ignored altogether. One notable exception is the recognition of the importance of top carnivores and major herbivores in driving ecosystem structure and function; this has led to controversial suggestions for "Pleistocene rewilding", which would involve introductions of exotic predators and herbivores (Caro 2007). We have only recently gained an appreciation of the disturbance regime (frequency, severity, size and selectivity of mortality-inducing events) as an agent of diversity and ecosystem maintenance, not just an agent of destruction (Kuuluvainen 2002, Beatty and Owen 2005).

The portfolio of restoration approaches apparent in our review of the literature exemplifies a rather young discipline, one still pre-occupied with trees and plants rather than taking a true ecosystem-based approach, and one in which success in meeting objectives is not yet routine. In many cases, we can say restoration practitioners are employing the "build it and they will come" model, with faith placed in establishing tree cover as a means of facilitating all aspects of forest ecosystem recovery and restoration. Although there is some basis for this faith, forest restoration in many parts of the world also requires concerted efforts to diversify the composition and structure of managed forests that were already successfully established as fully stocked stands of trees (Kuuluvainen et al. 2002, Douglas and Burton 2005, Fischer and Fischer 2006).

Illustrating that forest restoration is much more than planting trees, we now see cases where forest restoration involves the removal of trees to counteract the inherent ability of sites to grow vigorous stands of trees. Examples include the intensively managed forests of Europe in which uneven stand structures and dead wood are being promoted (Kuuluvainen et al. 2002, Hahn et al. 2005, Lilja et al. 2005, Fischer and Fischer 2006), and forest glades and meadows in eastern North America (e.g., Chan and Packer 2006, Pfitsch and Williams 2009) and pine forests of the southern USA (Moore et al. 1999, Allen et al. 2002, Varner et al. 2005) that are suffering from forest ingrowth in the absence of fire. In some parts of the world, forest restoration starts with the removal or replacement of exotic tree species, such as *Tamarix* spp. in the riparian forests of the southwestern USA (Harms and Hiebert 2006), adventive *Prunus serotina* and plantations of conifers in regions of Europe that supported beech, oak, or lime forests in the pre-industrial era (see several chapters in Stanturf and Madsen 2005).

Rehabilitating the composition of forest stands away from exotic tree species to dominance by native species suitable for the site and climate is one of the most widely applied and easily executed means of restoring compositional naturalness. There is also increasing consideration of understory plant species composition, including the removal of shade-tolerant exotic understory species (e.g., *Alliaria petiolata* in eastern North America; Nuzzo 1991), and the establishment of a full complement of native understory plant species (Grant 2006). Soil amelioration treatments are appropriate where native topsoil has been removed or degraded; wildlife habitat enhancement and dead wood introduction are undertaken where those attributes are deficient; herbivore control or the manipulation of forest age structure is conducted where those components of the ecosystem dominate at the expense of diversity. One size does not fit all, and every prescription will always have to draw from a broad toolbox to meet site- and situation-specific objectives (Brown et al. 2004).

It is not clear whether any of the methods or objectives we identified more strongly favour "naturalness" than any other. While spontaneous recovery and succession may be more natural by virtue of requiring no intervention, there are many instances where strong interventions (through soil reconstruction, re-introducing species, or disturbance regime management) are required in order to reinstate ecosystem composition, structure and function that better matches the pre-degradation condition. Although there are gaps in our knowledge and experience in restoring various dimensions of naturalness, forest restoration nonetheless has much to offer to and learn from other aspects of forest management.

4.2 Suggestions for Researchers and Managers

This review has exposed some weaknesses in the manner in which forest restoration is generally undertaken. Foremost among these is the frequent lack of clear goals, objectives and priorities in restoration (Sayer et al. 2004). When simple tree cover is considered the inherent objective, then apparent success often belies an incomplete provision of more subtle attributes that are valued or expected by others. Successful tree plantations, and their ability to provide fuelwood and watershed protection, may be exactly what is desired in some places, while it is the rehabilitation and diversification of successful plantations that is required for biodiversity conservation elsewhere. This means that completely different indicators are needed to evaluate progress towards different sets of restoration objectives. Likewise, terminology needs to be clearly and consistently applied. For example, is "weed removal" undertaken to reduce competitive pressure, or as part of a program for controlling exotic species? Work promoting the successful introduction of a wide array of species other than plants (fungi, bacteria, animals) as important ecosystem components needs to continue. To this end, the employment of fresh forest seed banks could be explored further, as employed in some mine reclamation programs where soil salvage can be incorporated into regular operations. Heterogeneity in composition, structure and pattern needs to be accommodated, not only to better approach natural variability, but also as a strategy of pro-active adaptation in anticipation of changing climatic conditions.

Establishment of restoration targets is highly site- and situation- dependent and will continue to be challenging. The restoration ecologist is charged with creating the conditions for success and then monitoring progress into an inherently unpredictable future. Articulation of clear restoration objectives that are linked to broadly-defined "desired" and "acceptable" outcomes will be important for monitoring progress and reporting on success of restoration initiatives.

Forest restoration is a long-term process, especially when its goal is old growth or primeval forest conditions. Ongoing maintenance, diversification and monitoring are consequently paramount. A median evaluation time of four years (Fig. 3) is inadequate for all but a few initial treatments; much longer programs of adaptive management and retrospective analysis are clearly needed. Given the great expense of forest reconstruction or rehabilitation, it is surprising that costs and cost efficiencies are rarely reported and compared. In like manner, evaluating the true efficacy of restorative treatments requires untreated controls in which spontaneous recovery and ecosystem dynamics are allowed to proceed. Such experimental controls are important for purposes of demonstration, ongoing research, and also as a potential cost-effective treatment option. There is a growing body of evidence that, in some situations, unaided recovery may promote more diverse ecosystems (Pensa et al. 2004) and that intensive restoration treatments may actually inhibit or slow ecosystem recovery (Sampaio et al. 2007). Finally, future reviewers need to be aware that the motives and objectives for a particular research project on forest restoration are often a limited subset of (or may even be completely different from) the reasons and expectations behind the operational restoration program with which it is associated.

5 Conclusions

Forest restoration is a form of forest management. This is a strong conclusion derived from even a cursory evaluation of the objectives, methods, and results of forest restoration undertaken over history. As such, forest restoration cannot be construed as a "hands off" approach to ecosystem management or conservation, nor one that necessarily has a "lighter touch" than other forms of forest manipulation such as those associated with industrialized timber management. Many people consider ecosystem restoration to be one of the core activities or options associated with ecosystem-based management (Yaffee 1999, Moore et al. 1999), and have called for its integration with the conservation-based management of degraded ecosystems (Noss et al. 2006). Naturalness is a multi-dimensional gradient (Brunson 2000, Machado 2004, Froude et al. 2010). Our conclusion from the literature is that much progress can be made and is being made in nudging forests towards more natural states and even to more natural processes in some instances. Restoration activities may need to be rather intrusive, with repeated treatments or maintenance before the restored ecosystem is self-sustaining and meets the desired objectives. Nevertheless, the result of most successful forest restoration efforts is a forest condition that can be recognized as "more natural" and is characterized by natural processes previously absent from the site. This work is incremental, and moves mostly in very small steps; only time will tell how effective our interventions are, and how robust they are under a changing climate. The degree to which this new configuration of trees and other organisms is persistent or sustainable in the long term depends on how well the restored ecosystem is suited to the current environmental conditions prevailing at the site and with changing climate. However, a lack of concrete targets for complete naturalness or a primeval state need not hobble our restoration efforts.

Setting targets or trajectories for restoration will always be extremely difficult because of the heterogeneity and dynamics of forest ecosystems. Efforts to restore naturalness in forests must accept that ecosystems are in continuous flux and should focus more on: restoration of the ecological processes underlying ecosystem structure and function (Stanturf et al. 2001); recovery from what we can easily identify as degraded states (e.g., deforestation, invasive species, atmospheric pollution); and restoration trajectories that accommodate future change (Jackson and Hobbs 2009). As with forest management in general, forest restoration constitutes a series of decisions that, through active intervention, promote certain forest values (and hence certain forest compositions, structures and functions) over others. This means that some dimensions of naturalness may or may not be embraced, while still promoting general improvements in the re-establishment or maintenance of healthy forest ecosystems.

Government policies and regulations can make a big difference in the degree to which, and sometimes the manner in which, forest restoration is undertaken. Several examples have resulted in massive programs of reforestation and forest rehabilitation: the Surface Mining Control and Reclamation Act of 1977 in the USA (Rodrique and Burger 2001), the 1995–2002 watershed restoration program in British Columbia, Canada (Douglas and Burton 2005), and the European Economic Community's removal of some agricultural subsidies in 2002, thereby initiating a conversion of millions of hectares of farmland to woodland (Fischer and Fischer 2006). On the other hand, grassroots efforts at forest restoration are undertaken around the world with few incentives from government or little guidance by professionals. Examples include the restoration of mangroves by Philippine fishing villagers to provide storm protection, fuelwood, and nursery habitat for fish (Walters 2000), and the widespread mobilization of volunteers to undertake savanna and woodland restoration in Illinois, USA (Miles et al. 1998).

Perhaps the greatest challenge to restoration of naturalness in forest ecosystems is the social and political will required to undertake restoration efforts that seriously embrace the stochasticity and temporal and spatial heterogeneity of natural forests. Incorporation of such variability will be difficult if we are constrained to small landscapes and short time-spans. Further, natural forests encompass a wide range of variation, including conditions that may not be considered desirable by land managers or by the public; thus it is important that forest restoration not be too constrained by administrative regulations and standards. Ultimately, human aesthetics, values and objectives will play a central role in setting objectives for restoration, making the whole concept of restoring naturalness somewhat of a paradox. Strategic direction for forest restoration ultimately requires a sociological context in setting priorities, directions, and expectations for land use, and a place-based articulation of the specific balance of values desired from each restoration project.

Acknowledgements

We thank the organizing committee of the PriFor 2010 conference for inviting us to prepare the two keynote presentations on which this paper is based. Constructive comments on earlier versions of this paper were provided by René Alfaro, Carla Burton, Brett Purdy, Brian Titus and two anonymous reviewers, for which we are grateful.

References

Ali, A.A., Asselin, H., Larouche, A.C., Bergeron, Y, Carcaillet, C. & Richard, P.J.H. 2008. Changes in fire regime explain the Holocene rise and fall of Abies balsamea in the coniferous forests of western Québec, Canada. The Holocene 18: 693–703.

Allen, C.D., Savage, M., Falk, D.A., Suckling, K.F., Swetnam, T.W., Schulke, T., Stacey, P.B., Morgan, P., Hoffman, M. & Klingel, J.T. 2002. Ecological restoration of Southwestern ponderosa pine ecosystems: a broad perspective. Ecological Applications 12: 1418–1433.

Allen, M.F., Allen, E.B. & Gómez-Pampa, A. 2005. Effects of mycorrhizae and nontarget organisms on restoration of a seasonal tropical forests in Quintana Roo, Mexico: factors limiting tree establishment. Restoration Ecology 13: 325–333.

Angermeier, P.L. 2000. The natural imperative for biological conservation. Conservation Biology 14: 373–381.

Armstrong, G.W. 1999. A stochastic characterization of the natural disturbance regime of the boreal mixedwood forest with implications for sustainable forest management. Canadian Journal of Forest Research 29: 424–433.

Asselin, H. & Payette, S. 2005a. Late Holocene opening of the forest tundra landscape in northern Québec, Canada. Global Ecology and Biogeography 14: 307–13.

— & Payette, S. 2005b. Late Holocene deforestation of a tree line site: estimation of pre-fire vegetation composition and black spruce cover using soil charcoal. Ecography 28: 801–805.

Barlow, J., Gardner, T.A., Araujo, I.S., Avila-Pires, T.C., Bonaldo, A.B., Costa, J.E., Esposito, M.C., Ferreira, L.V., Hawes, J., Hernandez, M.I.M., Hoogmoed, M.S., Leite, R.N., Lo-Man-Hung, N.F., Malcolm, J.R., Martins, M.B., Mestre, L.A.M., Miranda-Santos, R., Nunes-Gutjahr, A.L., Overal, W.L., Parry, L., Peters, S.L., Ribeiro-Junior, M.A., da Silva, M.N.F., da Silva Motta, C. & Peres, C.A. 2007. Quantifying the biodiversity value of tropical primary, secondary, and plantation forests. Proceedings of the National Academy of Sciences 104: 18555–18560.

Batho, A. & Garcia, O. 2006. De Perthuis and the origins of site index: a historical note. Forest Biometry, Modelling and Information Sciences 1: 1–10. Available at: http://forestgrowth.unbc.ca/. [Cited 17 Nov 2010].

Beatty, S.W. & Owen, B.S. 2005. Incorporating disturbance into forest restoration. In: Stanturf, J.A. & Madsen, P. (eds.). Restoration of boreal and temperate forests. CRC Press, Boca Raton, Florida, U.S.A. p. 61–76.

Berg, E.E., McDonnell Hillman, K., Dial, R. & DeRuwe, A. 2009. Recent woody invasion of wetlands on the Kenai Peninsula Lowlands, south-central Alaska: a major regime shift after 18,000 years of wet Sphagnum-edge peat recruitment. Canadian Journal of Forest Research 39: 2033–2046.

Bergeron, Y. & Archambault, S. 1993. Decreasing frequency of forest fires in the southern boreal zone of Quebec and its relation to global warming since the end of the 'Little Ice Age'. The Holocene 3: 255–59.

Björse, G. & Bradshaw, R. 1998. 2000 years of forest dynamics in southern Sweden: suggestions for forest management. Forest Ecology and Management 104: 15–26.

Bradshaw, R.H.W. & Holmqvist, B.H. 1999. Danish forest development during the last 3000 years reconstructed from regional pollen data. Ecography 22: 53–62.

— , Wolf, A. & Moller, P.F. 2005. Long-term succession in a Danish temperate deciduous forest. Ecography 28: 157–164.

Brown, R.T., Agee, J.K. & Franklin, J.F. 2004. Forest restoration and fire: principles in the context of place. Conservation Biology 18: 903–912.

Brubaker, L.B., Higuera, P.E., Rupp, T.S., Olson, M.A., Anderson, P.M. & Hu, F.S. 2009. Linking sediment-charcoal records and ecological modeling to understand causes of fire-regime change in boreal forests. Ecology 90: 1788–1801.

Brunson, M.W. 2000. Managing naturalness as a continuum: setting limits of acceptable change. In: Gobster, P.H. & Hull, R.B. (eds.). Restoring nature: perspectives from the social sciences and humanities. Island Press, Washington, D.C. , U.S.A. p. 229–244.

Bryant, D., Nielsen, D. & Tangley, L. 1997. The last frontier forests: ecosystems and economies on the edge. World Resources Institute, Washington, D.C., U.S.A.

Burton, P.J. 1998. An assessment of silvicultural practices and forest policy in British Columbia from the perspective of restoration ecology. In: Egan, B. (ed.). Helping the land heal: ecological restoration in British Columbia conference proceedings. B.C. Environmental Network Educational Foundation, Vancouver, British Columbia, Canada. p. 173–178.

— 2005. Ecosystem management and conservation biology. In: Watts, S.B. & Tolland, L. (eds.). Forestry Handbook for British Columbia, Fifth Edition. Faculty of Forestry, University of British Columbia, Vancouver, British Columbia, Canada. p. 307–322.

— 2010. Striving for sustainability and resilience in the face of unprecedented change: the case of the mountain pine beetle outbreak in British Columbia. Sustainability 2: 2403–2423.

Canham, C.D., Papaik, M.J. & Latty, E.F. 2001. Interspecific variation in susceptibility to windthrow as a function of tree size and storm severity for northern temperate tree species. Canadian Journal of Forest Research 31: 1–10.

Caro, T. 2007. The Pleistocene re-wilding gambit. Trends in Ecology and Evolution 22: 281–283.

Carcaillet, C., Bergeron, Y., Richard, P.J.H., Fréchette, B., Gauthier, S. & Prairie, Y.T. 2001. Change of fire frequency in the eastern Canadian boreal forest during the Holocene: does vegetation composition or climate trigger the fire regime? Journal of Ecology 89: 930–946.

Chan, P.K. & Packer L. 2006. Assessment of potential Karner Blue butterfly (Lycaeides melissa samuelis) (Family: Lycanidae) reintroduction sites in Ontario, Canada. Restoration Ecology 14: 645–652.

Conedera, M., Tinner, W., Neff, C., Meurer, M., Dickens, A.F. & Krebs, P. 2009. Reconstructing past fire regimes: methods, applications, and relevance to fire management and conservation. Quaternary Sciences Reviews 28: 555–576.

Dale, V.H., Swanson, F.J. & Crisafulli, C.M. (eds.). 2005. Ecological responses to the 1980 eruption of Mount St. Helens. Springer, New York, U.S.A.

Douglas, T. & Burton, P.J. 2005. Integrating ecosystem restoration into forest management in British Columbia, Canada. In: Stanturf, J.A. & Madsen, P. (eds.). Restoration of boreal and temperate forests. CRC Press, Boca Raton, Florida, U.S.A. p. 423–444.

Ellison, A.M., Bank, M.S., Clinton, B.D., Colburn, E.A., Elliott, K., Ford, C.R., Foster, D.R., Kloeppel, B.D., Knoepp, J.D., Lovett, G.M., Mohan, J., Orwig, D.A., Rodenhouse, N.L., Sobczak, W.V., Stinson, K.A., Stone, J.K., Swan, C.M., Thompson, J., Von Holle, B. & Webster, J.R. 2005. Loss of foundation species: consequences for the structure and dynamics of forested ecosystems. Frontiers in Ecology and the Environment 3: 479–486.

FAO (Food and Agriculture Organization). 2009. State of the world's forests 2009, Annex Tables 1 and 2. Food and Agriculture Organization of the United Nations. Rome, Italy. Available at: http://www.fao.org/docrep/011/i0350e/i0350e00.HTM. [Cited 25 Jul 2010].

Fischer, A. & Fischer, H. 2006. Restoration of forests. In: van Andel, J. & Aronson, J. (eds.). Restoration ecology. Blackwell Publishing, Malden, Massachusetts, U.S.A. p. 124–140.

Flannigan, M.D., Logan, K.A., Amiro, B.D., Skinner, W.R. & Stocks, B.J. 2005. Future area burned in Canada. Climatic Change 72: 1–16.

Floyd, D.W. 2002. Forest sustainability: the history, the challenge, the promise. The Forest History Society, Durham, North Carolina, U.S.A.

Froude, V.A., H.G. Rennie & Bomman, G.F. 2010. The nature of natural: defining natural character for the New Zealand context. New Zealand Journal of Ecology 34: 332–341.

George, T.L. & Zack, S. 2001. Spatial and temporal considerations in restoring habitat for wildlife. Restoration Ecology 9: 272–279.

Gilman, S.E., Urban, M.C., Tewksbury, J., Gilchrist, G.W. & Holt, R.D. 2010. A framework for community interactions under climate change. Trends in Ecology and Evolution 25: 325–331.

Gimmi, U., Wohlgemuth, T., Rigling, A., Hoffmann, C.W. & Bürgi, M. 2010. Land-use and climate change effects in forest compositional trajectories in a dry Central-Alpine valley. Annals of Forest Science 67: article 701. DOI: 10.1051/forest/2010026.

Girardin, M.P., Ali, A.A., Carcaillet, C., Mudelsee, M., Drobychev, I., Hély, C. & Bergeron, Y. 2009. Heterogeneous response of circumboreal wildfire risk to climate change since the early 1900s. Global Change Biology 15: 2751–2769.

— , Raulier, F., Bernier, P.Y. & Tardif, J.C. 2008. Response of tree growth to a changing climate in boreal central Canada: a comparison of empirical, process-based, and hybrid modelling approaches. Ecological Modelling 213: 209–228.

Glenn-Lewin, D.C., Peet, R.K. & Veblen, T.T. (eds.). 1992. Plant succession. Chapman and Hall, New York, U.S.A.

Gomez-Aparicio, L. 2009. The role of plant interactions in the restoration of degraded ecosystems: a meta-analysis across life-forms and ecosystems. Journal of Ecology 97: 1202–1214.

Grant, C.D. 2006. State-and-transition model for bauxite mining rehabilitation in the jarrah forest of Western Australia. Restoration Ecology 14: 28–37.

Greene, D.F., Macdonald, S.E., Haeussler, S., Domenicano, S., Noël, J., Jayen, K., Charron, I., Gauthier, S., Hunt, S., Gielau, E.T., Bergeron, Y. & Swift, L. 2007. The reduction of organic-layer depth by wildfire in the North American boreal forest and its effect on tree recruitment by seed. Canadian Journal of Forest Research 37: 1012–1023.

Grime, J.P. 2002. Plant strategies, vegetation processes, and ecosystem properties, second edition. John Wiley & Sons, Cichester, U.K.

Hahn, K., Emborg, J., Larson, J.B. & Madsen, P. 2005. Forest rehabilitation in Denmark using nature-based forestry. In: Stanturf, J.A. & Madsen, P. (eds.). Restoration of boreal and temperate forests. CRC Press, Boca Raton, Florida, U.S.A. p. 299–317.

Harms, R.S. & Hiebert, R.D. 2006. Vegetation response following invasive tamarisk (Tamarix spp.) removal and implications for riparian restoration. Restoration Ecology 14: 461–472.

Harris, J.A., Hobbs, R.J., Higgs, E. & Aronson, J. 2006. Ecological restoration and global climate change. Restoration Ecology 14: 170–176.

Hayes, J.J. & Robeson, S.M. 2009. Spatial variability of landscape pattern change following a ponderosa pine wildfire in northwestern New Mexico, USA. Physical Geography 30: 410–429.

Herault, B., Honnay, O. & Thoen, D. 2005. Evaluation of the ecological restoration potential of plant communities in Norway spruce plantations using a life-trait based approach. Journal of Applied Ecology 42: 536–545.

Higgs, E. 2003. Nature by design: people, natural process, and ecological restoration. MIT Press, Cambridge, Massachusetts, U.S.A.

Hobbs, R.J., Higgs, E. & Harris, J.A. 2009. Novel ecosystems: implications for conservation and restoration. Trends in Ecology & Evolution 24: 599–605.

IUCN (International Union for the Conservation of Nature). 2002. Investing in people and nature: IUCN Demonstration portfolio on forest landscape restoration. Case studies on Finland, Malaysia, Mexico, Nepal, Senegal, Tanzania, United Kingdom. Link: http://www.unep-wcmc.org/forest/restoration/globalpartnership/docs/portfolio.pdf .

Jackson S.T. & Hobbs, R.J. 2009. Ecological restoration in the light of ecological history. Science 325: 567–569.

Jacquemyn, H., Butaye, J. & Hermy, M. 2003. Impacts of restored patch density and distance from natural forests on colonization success. Restoration Ecology 11: 417–423.

Jasinski, J.P.P. & Payette, S. 2005. The creation of alternative stable states in the southern boreal forest, Québec, Canada. Ecological Monographs 75: 561–583.

Jenkins, C.N. & Joppa, L. 2009. Expansion of the global terrestrial protected area system, Biological Conservation 142: 2166–2174.

Johnson, E.A. 1992. Fire and vegetation dynamics – studies from the North American boreal forest. Cambridge University Press, New York, U.S.A.

Johnstone, J.F. & Chapin, F.S. 2003. Non-equilibrium succession dynamics indicate continued northern migration of lodgepole pine. Global Change Biology 9: 1401–1409.

— & Chapin, F.S. 2006. Effects of soil burn severity on patterns of post-fire tree recruitment in boreal forests. Ecosystems 9: 14–31.

— , Hollingsworth, T.N., Chapin, F.S. & Mack, M.C. 2010. Changes in fire regime break the legacy lock on successional trajectories in Alaskan boreal forest Global Change Biology 16: 1281–1295.

Kernaghan, G., Hambling, B., Fung, M. & Khasa, D. 2002. In vitro selection of boreal ectomycorrhizal fungi for use in reclamation of saline-alkaline habitats. Restoration Ecology 10: 43–51.

Koch, J.M. & Hobbs, R.J. 2007. Synthesis: Is Alcoa successfully restoring a native jarrah forest ecosystem after bauxite mining in Western Australia? Restoration Ecology 15: S137–S144.

Kuuluvainen, T. 2002. Disturbance dynamics in boreal forests: defining the ecological basis of restoration and management of biodiversity. Silva Fennica 36: 5–11.

— 2009. Forest management and biodiversity conservation based on natural ecosystem dynamics in Northern Europe: The complexity challenge. Ambio 38: 309–315.

— , Aapala, K., Ahlroth, P., Kuusinen, M., Lindholm, T., Sallantaus, T., Siitonen, J. & Tukia, H. 2002. Principles of ecological restoration of boreal forested ecosystems: Finland as an example. Silva Fennica 36: 409–422.

Landres, P.B., Morgan, P. & Swanson, F.J. 1999. Overview of the use of natural variability concepts in managing ecological systems. Ecological Applications 9:1179–1188.

Lenz, R. & Haber, W. 1992. Approaches for the restoration of forest ecosystems in northeastern Bavaria. Ecological Modelling 63: 299–317.

Lieffers, V.J., Messier, C., Burton, P.J., Ruel, J.-C. & Grover, B.E. 2003. Nature-based silviculture for sustaining a variety of boreal forest values. In: Burton, P.J., Messier, C., Smith, D.W. & Adamowicz, W.L. (eds.). Towards sustainable management of the boreal forest. NRC Research Press, Ottawa, Ontario, Canada. p. 481–530.

Lilja, S., de Chantal, M., Peterson, C., Kuuluvainen, T., Vanha-Majamaa, I. & Puttonen, P. 2005. Restoring natural characteristics in boreal Norway spruce (Picea abies L. Karst) stands with partial cutting, deadwood creation and fire: immediate treatment effects. Scandinavian Journal of Forest Research 20 (Suppl. 6): 68–78.

Lortie, C.J., Aarssen, L.W., Budden, A.E., Koricheva, J.K., Leimu, R. & Tregenza, T. 2007. Publication bias and merit in ecology. Oikos 116: 1247–1253.

Luyssaert, S., Schulze, E.-D., Börner, A., Knohl, A., Hessenmöller, Law, B.E., Ciais, P., & Grace, J. 2008. Old-growth forests as global carbon sinks. Nature 455: 213–215.

Machado, A. 2004. An index of naturalness. Journal for Nature Conservation 12: 95–110.

Maginnis, S. & Jackson, W. 2002. Restoring forest landscapes: Forest landscape restoration aims to re-establish ecological integrity and enhance human well-being in degraded forest landscapes. ITTO Tropical Forest Update 12/4: 9–11. Available at: http://www.itto.or.jp/live/Live_Server/185/tfu.2002.04(09-11).e.pdf. [Cited 20 Sept. 2011].

Miles, I., Sullivan, W.C. & Kuo, F.E. 1998. Ecological restoration volunteers: the benefits of participation. Urban Ecosystems 2: 27–41.

Millar, C.I., Stephenson, N.L. & Stephens, S.L. 2007. Climate change and forests of the future: managing in the face of uncertainty. Ecological Applications 17: 2145–2151.

Mooney, H.A. & Hobbs, R.J. 2000. Invasive species in a changing world. Island Press, Washington, D.C., U.S.A.

Moore, M.M., Covington, W.W. & Fulé, P.Z. 1999. Reference conditions and ecological restoration: a southwestern ponderosa pine perspective. Ecological Applications 9: 1266–1277.

Morin, X. & Thuiller, W. 2009. Comparing niche- and process-based models to reduce prediction uncertainty in species range shifts under climate change. Ecology 90: 1301–1313.

— , Viner, D. & Chuine, I. 2008. Tree species range shifts at a continental scale: new predictive insights from a process-based model. Journal of Ecology 96: 784–794.

National Forestry Database (Canada). [On-line database]. Available at http://nfdp.ccfm.org/fires/jurisdictional_e.php. [Cited 8 Nov 2010].

Niklasson, M., Zin, E., Zielonka, T., Feijen, M., Korczyk, A.F., Churski, M., Samojlik, T., Jedrzejewska, B., Gutowski, J.M. & Brzeziecki, B. 2010. A 350-year tree-ring fire record from Bialowieza Primeval Forest, Poland: implications for Central European lowland fire history. Journal of Ecology 98: 1319–1329.

Noss, R.F., Beier, P., Covington, W.W., Grumbine, R.E., Lindenmayer, D.B., Prather, J.W., Schmiegelow, F., Sisk, T.D. & Vosick, D.J. 2006. Recommendations for integrating restoration ecology and conservation biology in ponderosa pine forests of the southwestern United States. Restoration Ecology 14: 4–10.

Nuzzo, V.A. 1991. Experimental control of garlic mustard [Alliaria petiolata (Bieb.) Cavara and Grande] in northern Illinois using fire, herbicide and cutting. Natural Areas Journal 11: 158–167.

Paine, R.T., Tegner, M.J. & Johnson EA. 1998. Compounded perturbations yield ecological surprises. Ecosystems 1: 535–545.

Parisien, M.-A. & Moritz, M.A. 2009. Environmental controls on the distribution of wildfire at multiple spatial scales. Ecological Monographs 79: 127–154.

Pensa, M., Sellin, A., Luud, A. & Valgma, I. 2004. An analysis of vegetation restoration on opencast oil shale mines in Estonia. Restoration Ecology 12: 200–206.

Peterken, G.F. 1996. Natural woodland; ecology and conservation in northern temperate regions. Cambridge University Press, Cambridge, U.K.

Pfitsch, W.A. & Williams, E.H. 2009. Habitat restoration for lupine and specialist butterflies. Restoration Ecology 17: 226–233.

Pickett, S.T.A., Collins, S.C. & Armesto, J.J. 1987. Models, mechanisms and pathways of succession. Botanical Review 53: 335–371.

— , Cadenasso, M.L. & Meiners, S.J. 2009. Ever since Clements: from succession to vegetation dynamics and understanding to intervention. Applied Vegetation Science 12: 9–21.

Primack, R.B. 2006. Essentials of conservation biology, fourth edition. Sinauer Associates, Sunderland, Massachusetts.

Restrepo, C., Walker, L.R., Shiels, A.B., Bussmann, R. Claessens, L., Fisch, S., Lozano, P., Negi, G., Paolini, L., Poveda, G., Ramos-Scharron, C., Richter, M. & Velazquez, E. 2009. Landsliding and its multiscale influence on mountainscapes. BioScience 59: 685–698

Rodrigue, J.A. & Burger, J.A. 2001. Forest soil productivity of mined land in the midwestern and eastern coalfield regions. Soil Science Society of America Journal 68: 833–844.

Sampaio, A.B., Holl, K.D. & Scariot, A. 2007. Does restoration enhance regeneration of seasonal deciduous forests in pastures in Central Brazil? Restoration Ecology 15: 462–471.

SAS Institute 2010. SAS/STAT 9.2 User's guide – procedures. SAS Institute. Cary, North Carolina, U.S.A. Available at: http://support.sas.com/documentation/onlinedoc/stat/. [Cited 17 Nov 2010].

Sayer, J., Chokkalingam, U. & Poulsen, J. 2004. The restoration of forest biodiversity and ecological values. Forest Ecology and Management 201: 3–11.

Schelhaas, M.J., Nabuurs, G.J. & Schuck, A. 2003. Natural disturbances in the European forests in the 19th and 20th centuries. Global Change Biology 9: 1620–1633.

Schnitzler, A. & Borlea, F. 1998. Lessons from natural forests as keys for sustainable management and improvement of naturalness in managed broadleaved forests. Forest Ecology and Management 109: 293–303.

Schumacher, S. & Bugmann, H. 2006. The relative importance of climatic effects, wildfires and management for future forest landscape dynamics in the Swiss Alps. Global Change Biology 12: 1435–1450.

SERI (Society for Restoration International). 2004. The SER international primer on ecological restoration. Science & Policy Working Group, Society for Ecological Restoration International. Tucson, Arizona, U.S.A. Available at: www.ser.org. [Cited 22 Nov 2010].

Shorohova, E., Kuuluvainen, T., Kangur, A., & Jõgiste, K. 2009. Natural stand structures, disturbance regimes and successional dynamics in the Eurasian boreal forests: a review with special reference to Russian studies. Annals of Forest Science 66: 201. DOI: 10.1051/forest/2008083.

Shuman, B., Henderson, A.K., Plank, C., Stefanova, I. & Ziegler, S. 2009. Woodland-to-forest transition during prolonged drought in Minnesota after ca. AD 1300. Ecology 90: 2792–2807.

Smith, D.M. 1986. The practice of silviculture. 8th edition. Wiley, New York, U.S.A.

Stanturf, J.A. & Madsen, P. 2002. Restoration concepts for temperate and boreal forests of North America and Western Europe. Plant Biosystems 16: 143–158.

— & Madsen, P. (eds.). 2005. Restoration of boreal and temperate forests. CRC Press, Boca Raton, Florida, U.S.A.

— , Schoenholtz, S.H., Schweitzer, C.J. & Shepard, J.P. 2001. Achieving restoration success: myths in bottomland hardwood forests. Restoration Ecology 9: 189–200.

Svenning J.C., Baktoft K.H. & Balslev, H. 2009. Land-use history affects understorey plant species distributions in a large temperate-forest complex, Denmark. Plant Ecology 201: 221–234.

Swetnam, T.W., Allen, C.D. & Betancourt, J.L. 1999. Applied historical ecology: using the past to manage for the future. Ecological Applications 9: 1189–1206.

Tang, G.P. & Bartlein, P.J. 2008. Simulating the climatic effects on vegetation: approaches, issues and challenges. Progress in Physical Geography 32: 543–556.

Taylor, A.R., Chen, H.Y.H. & VanDamme L. 2009. A review of forest succession models and their suitability for forest management planning. Forest Science 55: 23–36.

Turner M.G., Romme, W.H., Gardner R.H. & Hargrove, W.W. 1997. Effects of fire size and pattern on early succession in Yellowstone National Park. Ecological Monographs 67: 411–433.

Ulanova, N.G. 2000. The effects of windthrow on forests at different spatial scales: a review. Forest Ecology and Management 135: 155–167.

Varner, J.M., Gordon, D.R., Putz, F.E & Hiers, J.K. 2005. Restoring fire to long-unburned Pinus palustris ecosystems: novel fire effects and consequences for long-unburned ecosystems. Restoration Ecology 13: 536–544.

Walters, B.B. 2000. Local mangrove planting in the Philippines: are fisherfolk and fishpond owners effective restorationists? Restoration Ecology 8: 237–246.

Yaffee, S.L. 1999. Three faces of ecosystem management. Conservation Biology 13: 713–725.

Zielonka, T. Holeksa, J., Fleischer, P. & Kapusta, P. 2010. A tree-ring reconstruction of wind disturbances in a forest of the Slovakian Tatra Mountains, Western Carpathians. Journal of Vegetation Science 21: 31–42.

Total of 117 references