Sustainability in multi-aged stands: an analysis of long-term plenter systems

KEVIN L. O’HARA¹*, HUBERT HASENAUER² AND GEORG KINDERMANN²

¹Department of Environmental Science, Policy and Management, University of California – Berkeley, 137 Mulford Hall, Berkeley, CA 94720-3114, USA
²Department of Forest and Soil Sciences, University of Natural Resources and Applied Life Sciences, Peter Jordan Strasse 82, A-1190 Vienna, Austria
*Corresponding author. E-mail: ohara@nature.berkeley.edu

Summary

Long-term research plots in multi-aged stands managed with the plenter system were assessed to evaluate sustainability of the plenter system in Central Europe. Plots primarily consisted of Norway spruce (Picea abies (L.) Karst.), silver fir (Abies alba Mill.) or European beech (Fagus sylvatica L.) and were measured for seven to 16 measurement intervals over 60–91 years. Sustainability was assessed with four types of criteria: stand density, tree species diversity, basal area increment, and stand structure. Comparable even-aged stands were also analysed to compare and evaluate the performance of the measures of sustainability. Measures of species diversity, increment and stand structural diversity generally experienced increasing trends over time in these even-aged stands. Basal area generally increased and trees ha⁻¹ decreased in multi-aged stands following similar patterns as in even-aged stands. These results suggest that the plenter system is still evolving and is not the model of sustainability often assumed. Many of the measures used have potential as indicators of sustainability in multi-aged stands.

Introduction

Uneven-aged or selection systems are implemented for a variety of reasons, one of which is their apparent sustainability. This sustainability is assumed to be achieved through a relative steady state of structure and function over time as compared with even-aged systems. There is also a general perception that these systems are more natural (Larsen, 1995). As a result, uneven-aged systems (and the management approaches that encourage them) have been described as ‘close-to-nature’ (Mlinsek, 1996), ‘back-to-nature’ (Gamborg and Larsen, 2003), ‘diversity-oriented’ (Lähde et al., 1999), ‘near-natural’ (Benecke, 1996) and ‘nature-based’ (Bradshaw et al., 1994).

Sustainability is a central precept of forestry and therefore central to all silvicultural systems. The sustainability of stand management regimes is important as stands are the land unit for implementation in forestry. Even-aged stands fluctuate widely in stand characteristics over a rotation. Because each even-aged stand has a clear beginning and end point, their sustainability can be measured over discrete time intervals.

The assessment of sustainability of uneven-aged or multi-aged stands is difficult and requires criteria
and indicators that can be measured during stand development and are sensitive to the relatively small amount of variation in selection systems over time. In theory, selection or multi-aged stands function continuously without a beginning or end point with the cutting cycle being somewhat analogous to the even-aged rotation in terms of harvest treatments. Since variations in stand characteristics are small, it may take very long time periods to recognize the subtle changes or trends that indicate a system is not sustainable. Multi-aged systems may also vary with management objectives and from one ecosystem to another.

Long-term analyses of multi-aged management regimes provide implications for sustainability. Based on long-term data from plenter stands in Switzerland, Zingg et al. (1997) examined several criteria for sustainability including stand structure, increment and regeneration. Stand structure was represented with diameter distributions and dominant heights over time. Zingg et al. (1997) concluded that despite fluctuations in these characteristics, most stands had reached the desired equilibrium (Schütz, 1997a) and sustainability was assured.

In south-western Germany, Spiecker (1986) examined plenter stands over a 34-year period and noted a dramatic decrease in volume increment during the 1970s. Using similar data, Kenk (1995) looked at growth and yield trends in even-aged and uneven-aged stands in Central Europe. He reported the same reduction in volume increment in the 1970s as Spiecker (1986). In Sweden, Lundqvist (1991, 1993) used several long-term selection plots in Norway spruce (Picea abies (L.) Karst.) that ranged in age up to 63 years and found adequate regeneration but stand structure varied over time from plot to plot. This variation was apparently related to cutting patterns and also affected stocking.

Sendek et al. (2003) reported on 40-year results from mixed northern conifers in New England. They found increased proportions of red spruce (Picea rubens Sarg.) over time that were the intentional effects of management. This study generally looked at comparisons of treatments/cutting cycles rather than long-term trends. Using a group selection approach in New England broadleaved stands, Leak and Filip (1977) reported increased composition of less shade tolerant species. Another eastern North American study looked at sustainability in mixed mesophytic forests managed with a selection system over a 50-year period (Schuler, 2004). Species diversity declined over time and the trend in increment was downward, but was not statistically significant. All three of these studies appear to report conditions that are somewhat in transition: the former two studies experienced intentional shifts in species composition, whereas the third experienced reductions in species diversity that may result in significant reductions in increment.

In mixed-species forests in northern Japan, Yoshida et al. (2006) reported increased recruitment of shade tolerant broadleaved species following 20 years of selection harvesting. This selection system attempted to balance growth with harvests on a 10-year cutting cycle and was designed to develop a silvicultural system rather than test an established system.

In mixtures of loblolly pine (Pinus taeda L.) and shortleaf pine (Pinus echinata Mill.), several long-term studies have documented stand development under selection systems. Cain and Shelton (2001) found standing volume increased because cutting was less than periodic growth over a 53-year period. In a separate study, selection silviculture was used to demonstrate the potential for rehabilitation of degraded stands (Reynolds et al., 1984; Baker, 1986). Forty-one years after study initiation, both the degraded and the well-stocked stands were productive and producing adequate regeneration. Both of these studies experienced considerable fluctuation in the management regime due to variable effectiveness in controlling competing hardwood competition, administrative constraints in the 1970s and the rehabilitation objective in the latter study.

Historical background and objectives

With the industrialization and the population increases of the seventeenth and eighteenth centuries in Central Europe, the demand for timber, particularly of fuel wood, increased dramatically. As a result, overcutting and exploitation of forests were evident (Spiecker, 2000). The shortage of timber promoted short-rotation systems such as coppice systems or simply the cutting of remaining mature and valuable trees. Since this selective harvesting led to additional forest devastation,
it was considered to be unsustainable (Bühler, 1922). In the nineteenth century, France (in 1827) and southern Germany (in 1833) limited selective cutting by enforcing forest laws which promoted the clear-cut system. This management system implements the ‘normal forest’ idea according to Hundeshagen (1826) and Heyer (1841): at that time, it was considered as the only sustainable forest management system. Existing plenter forests were transformed to even-aged forests (see Dvorak, 2001).

With the rigorous enforcement of the clear-cut system, increased susceptibility to damage became more evident resulting in a debate about alternative forest management systems that included individual tree removals. Foresters like Anton Tichy, Adolphe Gurnaud and Henri Biiolley promoted the idea of single-tree selection (Schütz, 2001).

Central to this debate was the development of the so-called ‘control sampling method’ first proposed by Gurnaud (1878) and then further developed by Biiolley (1920), which provided a scientific method to control harvesting in what became known as plenter systems (see O’Hara and Gersonde (2004) for a discussion of different multi-aged systems). This inventory method collects information from repeated observations on permanent sample plots to calculate periodic volume increment. Although this method provided a scientific tool to control harvesting in multi-aged forests, the state forest services in Germany and France were strictly against a change in the management system since they feared again an uncontrolled overexploitation of forests similar to the Middle Ages (Röhrl, 1927).

Regular plenter forest management systems were developed only in specific regions across Europe. According to Schütz (2001), ~400 000 ha or 1.1–8.0 per cent of the regional forest area is currently managed according to the plenter system. The three main regions in Europe where the plenter system is applied are (1) the beech plenter forests in Central Germany; (2) the plenter forests in France, Switzerland (e.g. Emmental), southern Germany and Western Austria and (3) Slovenian mountains. The typical forest type is a silver fir (Abies alba Mill.) dominated mixed Norway spruce/beech (Fagus sylvatica L.) forest with a regular management system (Schütz, 1997b, 2001). The increasing interest in alternative management systems to clear-cutting has led to the adaptation of individual tree growth models specifically designed for managed uneven-aged, mixed-species stands (see Hasenauer, 2006).

The Montreal Process (http://www.mpci.org/criteria_e.html, accessed on 3 December 2006) identified criteria for forest biological diversity, productive capacity and maintenance of forest ecosystem health. These three criteria were addressed in this study by developing four types of indicators: (1) stocking, (2) species diversity, (3) increment and outgrowth and (4) stand structure.

For multi-aged stands, stocking should be relatively constant between cutting cycles as it represents growing stock. Downward trends in total growing stock can indicate excessive harvesting or problems securing adequate regeneration, whereas increasing trends can correspond to reductions in average tree growth and size. Both trends may also affect increment. Species composition should also be relatively constant as large fluctuations may indicate that the management regime is favouring certain species over others. A shift to shade tolerant species, for example, would indicate that stocking might be too high for regeneration and growth of less shade tolerant species. Increment should be constant between cutting cycles. Whereas the management regime and the resultant stand structure can affect increment and productivity, a constant management regime should result in a constant increment. This would be indicated by both constant increment and removals over time. Stand structure is often the primary component of the management regime because of its importance in multi-aged stocking control (O’Hara and Gersonde, 2004). It also fluctuates during a cutting cycle because of harvesting and growth. In multi-aged stands, stand structure affects increment (O’Hara, 1996) and probably also species composition.

Long-term research plots are scarce and studies with a continuity of management purpose even scarcer. Additionally, studies to establish sustainability are difficult because the studies themselves are often using an adaptive approach to determine appropriate levels for harvesting, stocking or species composition. Interaction between variables may also have a cascading effect: for example, an adjustment in harvesting intensity might affect subsequent stocking and species composition.

The objective of this study is to investigate and assess the sustainability of typical single-tree
selection of plenter forests in Switzerland. Data for this study come from long-term research plots with a documented management history. The specific working steps of this study can be summarized as follows:

1. Develop indicators for evaluating the sustainability of multi-aged stands with regard to four broad categories:
   a. stocking,
   b. species composition,
   c. increment and
   d. stand structure and

2. Evaluate these criteria and indicators using long-term data from plenter systems for mixed-species, multi-aged stands.

**Methods**

Data from a series of long-term research plots in Switzerland were used for this analysis. Zingg et al. (1997) used a similar collection of these plots for their analysis. These individual plots were variable in size, unreplicated and maintained for variable periods of time beginning early in the 1900s for most plots. Plot selection criteria required that plots were dominated by conifers, including Norway spruce or silver fir as primary species (Table 1). European beech was often present as an important constituent. Other requirements were that plots had a minimum of five measurement intervals with plot size no smaller than 0.25 ha. Even-aged plots were generally smaller than those for multi-aged stands because of greater stand uniformity in these structures (Table 1).

Diameter distributions of plots were examined to separate ‘even-aged and ‘multi-aged’ plots independent of external classifications. Diameter distributions that approached ‘normal’ were categorized as even-aged and those with distributions that approached negative exponential were multi-aged. Several plots included mixtures of Norway spruce and Swiss stone pine (Pinus cembra L.) covering both even-aged (plots 1, 2 and 3) and plenter stands (plots 14 and 15). These plots existed at higher elevations and lower site quality than the majority of plots. In total, 16 multi-aged and 11 even-aged plots were selected for this study (Table 1).

Tree measurements included diameters of all trees and a subsample of heights, and all trees were tagged. Site index was estimated based on the height of the 100 largest diameter trees per ha. A number of plots had no change in the number of trees per plot through the first two measurements. It was speculated that this was because the second measurement only measured the trees noted in the first measurement regardless of how many trees were present. For these plots, the first measurement was removed from the analyses and is not included in the range of measurements in Table 1.

**Sustainability criteria and indicators**

**Stocking**

The constancy of growing space occupancy was examined over the life of the research plots using trees ha$^{-1}$ and basal area ha$^{-1}$ for trees of minimum 5 cm diameter. In this study, stocking included all living trees present on the research plot at the time of measurement. Although the stocking will fluctuate from the beginning to the end of a cutting cycle in multi-aged stands (O’Hara and Valappil, 1999), the trend for both basal area ha$^{-1}$ and trees ha$^{-1}$ should otherwise be flat. In contrast, even-aged stands typically experience increasing basal area ha$^{-1}$ and decreasing trees ha$^{-1}$ during stand development.

**Species diversity**

In a sustainable system, the species composition and relative proportions of species should remain relatively constant over time. For even-aged systems, there would be expected fluctuations during stand development but if management were constant over time, the species composition would be constant from one rotation to the next. For multi-aged stands, the species composition would be expected to remain much more constant, perhaps fluctuating from one cutting cycle to the next.

In this analysis, species were classified into five groups: Norway spruce, silver fir, European beech, other conifer and other broadleaved species. Only tree species data were available in this dataset (minimum diameter 5 cm). Four diversity measures were used: (1) an $\alpha$ log series and (2) Shannon diversity for species richness, (3) Berger–Parker for species dominance and (4) Shannon evenness for species evenness (Table 2; Magurran, 1988). Each measure was calculated using numbers of trees/species and basal area/species. The $\alpha$ measure requires an iterative calculation and increases with increasing species richness.
Shannon’s diversity index ($H'_d$) is a frequently used measure that increases with species richness. A reciprocal form of Berger–Parker was used that increases with increasing diversity and decreasing dominance by a single species or species group (Table 2). A Berger–Parker value of 1.0 is the minimum and occurs in single-species stands. The Shannon evenness index ($E_d$) measures relative abundance of species groups and ranges from 0 to 1. A value of 1 indicates all species are equally abundant. Bagnaresi et al. (2002) used Shannon diversity ($H'$) and evenness ($E$) in their analysis of biodiversity in multi-aged Norway spruce/silver fir stands in the eastern Alps. Neumann and Starlinger (2001) also used these same measures on a variety of stand structures in Austria.

**Increment**
The productivity of the stand is most easily measured using increment. Stem volume increment is
the preferred measure because it is representative of stand utilization. In the data used in this study, the number of height measurements was limited, particularly in early years, and height measurement techniques were highly variable over time. To avoid data generation through height estimation from diameter for volume calculation, basal area increment was used as the primary dependent variable for assessing increment trends. Data on volume removals were not available, but the volume of trees absent in any remeasurement was described as ‘outgrowth’. These trees consisted of harvest removals and mortality. Although the exact fate of any ‘outgrowth tree’ cannot be certain, the high intensity management of these plots suggests that a very high proportion of these trees were removed in harvest treatments.

For multi-aged stands, increment would be expected to remain constant with minor fluctuations between cutting cycles (O’Hara and Valappil, 1999). The result is fluctuations in increment within a relatively narrow range during a cutting cycle, but no other variation. In contrast, the increment of an even-aged stand would increase rapidly early in stand development as growing stock builds and slows later in stand development.

**Stand structure**
The constancy of stand structure was measured with the Shannon diversity and Shannon evenness indices and the Gini coefficient. The two Shannon measures used numbers of trees in 5 cm size classes (Table 2). Shannon’s structural diversity measure \( H_s \) increases with increasing numbers of size classes (Staudhammer and LeMay, 2001). A multi-aged stand should therefore remain relatively constant over time, whereas an even-aged stand would typically have an increasing \( H_s \) with age as the stand develops a broader range of diameter size classes. The Shannon evenness index \( E_s \) varies from 0 to 1 with higher values representing stands with more equal numbers of trees.
per size class. $E_s$ would be expected to remain constant over time in multi-aged stands at a relatively high level. For even-aged stands, $E_s$ would increase as the range of diameters expands with stand development.

The Gini coefficient is a measure of size inequality (Weiner and Solbrig, 1984) that expresses inequality on a scale from 0 to 1 (Table 2). A stand with all trees of equal size would have a Gini coefficient of 0 and a stand with all trees but one with a value of zero would have a Gini coefficient of 1.0. Multi-aged stands would therefore be expected to have higher and more constant Gini coefficient values than even-aged stands. Lexerød and Eid (2006) used the Gini coefficient, Shannon $H$ and $E$, and other diversity measures on diameter distributions to assess diameter diversity for forest management planning in Norway spruce/Scots pine ($Pinus sylvestris$ L.) stands. They found the Gini coefficient to be superior to other measures tested and having potential for a wide variety of forest management applications.

Analysis procedures

The analyses in this study sought to determine if measures of sustainability for plenter stands were constant over time. All measures of sustainability were expressed graphically as time-series relationships. Measures of stocking, species diversity and stand structure were based on measurement dates. Stand increment and outgrowth were based on changes between measurement dates and were expressed as midpoints of measurement intervals. Therefore, for increment and outgrowth, time-series data included one less measurement than other analyses. Trends in time-series relationships were assessed with linear regression using the measure of sustainability as the dependent variable and date as the independent variable. The slope coefficient and its significance ($P < 0.05$) were used as an indication of either positive or negative trends in the sustainability measure over time. Because the slope coefficient in linear regression can be influenced by outliers, particularly at the beginning or end of the time series, a second linear regression procedure was used that removed outliers from the analysis. This procedure, termed ‘robust regression’ in this analysis, reduced the influence of outliers on the regression. Outliers were found by their influence on the regression. If the influence was high, the weight of the data point was reduced. Since the objective of these analyses was to quantify the trends in sustainability measures over time, significant slope coefficients and their direction were noted and tallied within stand structures (even-aged or multi-aged) for both regression procedures. Slopes were not averaged since this would have masked variation and within-plot trends. Results over all plots may therefore have included

1. plots with a high proportion of non-significant slopes indicating constancy in the sustainability measure,
2. plots with a large proportion of significant slopes but occurring as both positive and negative trends. This was assumed to indicate a high level of variation and change across plots in a sustainability measure but no substantive trends across plots in the direction of these trends and
3. plots where a large majority of slopes were significant and of the same direction indicating a strong positive or negative trend in this sustainability measure across all plenter system plots.

Analyses were performed over both the 16 plenter plots and the 11 even-aged plots. The intent was not to compare multi-aged and even-aged stands, but rather to use the even-aged plot trends to show the sensitivity of the sustainability measure in a substantially different stand structure.

Results

Stocking

Basal area ($m^2 \text{ ha}^{-1}$) increased and density (trees $\text{ha}^{-1}$) decreased in even-aged stands as expected over the analysis period (Figures 1 and 2, Table 3). Similar trends were observed in plenter plots for basal area but were less clear for density (Figures 1 and 2, Table 3). Many of the plenter plots increased in basal area during initial measurement periods; however, the robust regression procedure also indicated increasing trends in basal area over time. The average slope of the seven plots with significant positive relationships using the linear procedure (Table 3) was $0.10 \text{ m}^2 \text{ ha}^{-1} \text{ year}^{-1}$. 
Species diversity

Trends for species dominance as represented by the Berger–Parker index were weak or non-existent for multi-aged plots through the analysis period (Table 3). However, nearly all plots had significant slopes. Nine and 10 plots out of 11 had significant slopes for the Berger–Parker index using basal area and trees ha$^{-1}$, respectively. Even-aged plot trends were negative for the Berger–Parker index using basal area and positive for trees ha$^{-1}$. Twelve and 13 plenter plots had significant slopes with the robust regression procedure for the Berger–Parker index using basal area and trees ha$^{-1}$, respectively. The weakly positive trend for the Berger–Parker index using basal area for plenter stands indicates that individual species were increasing slightly in amount of basal area per species over time.

Species richness generally increased during the analysis period for multi-aged plots. However, the alpha index that was found to be too

Figure 1. Basal area over time for plenter and even-aged plots for selected study plots. Each line represents the trend over time for a single plot.
sensitive to minor fluctuations to use for long-term trends was not used further in these analyses. The slope in the Shannon $H'_d$ index was significant in nearly all plenter plots and was generally increasing (Figure 3, Table 3). These trends indicate an increasing number of species over time. For example, the average number of species/plot increased from 3.6 to 4.8 from beginning to end of the analysis period for the plenter plots. For even-aged plots, a weak trend was evident for Shannon $H'_d$ for basal area per species suggesting a weak decreasing trend in species richness. For species evenness, the Shannon $E_d$ indicated increasingly equal amounts of basal area and trees per species for both plenter and even-aged stands (Figure 4, Table 3). The trends were stronger for plenter than even-aged stands.

**Basal area increment and outgrowth**

Trends in basal area plot increment were highly variable over the analysis period. Plenter plots exhibited relatively constant patterns but increases in increment since the 1970s (Figure 5, Table 3).
When measurement intervals after 1970 were excluded, there were only three plots with significant slopes in the plenter plots (two negative, one positive). In the measurement intervals after 1970, basal area increment increased an average of 30.7 per cent over the 16 plenter plots. Even-aged plots had decreasing basal area increment over time as expected (Figure 5, Table 3). Basal area outgrowth was also highly variable over the analysis period (Figure 6). Few linear trends were apparent because of a general decline in outgrowth until approximately 1970 and an increasing trend after this point.

Stand structure

The Gini coefficient trends for multi-aged stands were generally increasing while even-aged trends were decreasing (Figure 7, Table 3). Higher values indicate greater size class diversity as would be expected in multi-aged stands. Exceptions to these trends were several even-aged plots that experienced dramatic increases in their Gini coefficient that corresponded to development of a second cohort as these stands entered the understory reinitiation stage (sensu Oliver, 1981).

The Shannon $H'_s$ for structural diversity had significant and positive coefficients for all 16 multi-aged plots (Figure 8, Table 3). Fifteen of the 16 plenter plots had more 5 cm diameter classes at the end of their measurement period (the 16th plot was unchanged) and mean number of 5 cm diameter classes for all plenter plots increased from 14.8 to 18.6 over the length of the analysis period. Even-aged plots also had increasing trends for Shannon $H'_s$. Size class evenness as represented by the Shannon $E_s$ was relatively constant for the multi-aged plots over the length of the analysis period (Table 3). This indicates the number of trees by size class was relatively constant over the diameter classes. There were no apparent patterns for the even-aged plots.

Discussion

A good measure of sustainability should be simple, reproducible, easily interpretable and responsive to factors that may indicate some change in sustainability. However, a single measure does not assure sustainability: instead, it provides a means to monitor certain aspects of sustainability over time and describe the stand conditions over time that contribute to sustainability.
Measures are needed that evaluate a diversity of functions in stand management. Although stand-level sustainability was emphasized in this study, these same concepts apply at other spatial scales. Ultimately, constancy in a criteria or indicator is needed at some timescale to establish sustainability for any forest management regime. In this study, we recognized four broad areas of function for multi-aged stands: stocking, species diversity, increment and stand structure.

Results indicated increasing trends for basal area over time in the plenter plots and a decrease in trees ha$^{-1}$. These are similar patterns as seen in the even-aged plots suggesting that an environmental effect may be the cause. However, the increase in numbers of large trees and in numbers of diameter classes indicated that the change was, at least in part, intentional. Patterns for basal area increment were relatively weak with more plenter plots exhibiting positive trends than

Figure 3. Shannon diversity index ($H'_d$) for species richness using basal area per species (top) and trees ha$^{-1}$ per species (bottom) for plenter stands. Each line represents the trend over time for a single plot.
negative. These positive trends in increment for plenter plots were in contrast to the patterns for even-aged stands.

Both increased species richness and evenness over time were observed for these plenter stands (Figures 3 and 4). The species diversity analyses here included only tree species and simplified tree species diversity into five categories. Information on understorey species would provide additional useful information on sustainability. Individual species categories – rather than the species groups used here – for the species diversity analyses would have resulted in much more erratic patterns in species diversity over time, but would have probably indicated more significant increases in richness over time as well. The separation into individual species would probably have resulted in a reduction in evenness.

The stand structure of these plenter stands is becoming more complex over time as represented

Figure 4. Shannon index ($E_d$) for species evenness using basal area per species (top) and trees ha$^{-1}$ per species (bottom) for plenter stands. Each line represents the trend over time for a single plot.
by a strong trend of greater numbers of diameter classes and its effect on the Shannon $H'_d$ (Figure 8). The greater number of diameter classes is the result of retention of larger trees in these stands over time. Twelve of 16 plots experienced significant changes in evenness and the Gini coefficient (Table 3, Figure 7). The data for structural evenness indicate a flatter distribution of basal area per size class in the eight plenter stands with increasing $E_s$. Four stands had a decreasing $E_s$ indicating the opposite trend. A large separation in the Gini coefficient between multi-aged and even-aged stands indicates potential of this measure as a classification tool (Figure 7).

Interestingly, trends for basal area and trees ha$^{-1}$ with a diameter at breast height greater than 5 cm were similar between even-aged and plenter plots, but increment and stand structure were different. This suggests increment may

*Figure 5. Basal area increment for plenter and even-aged plots. Each line represents the trend over time for a single plot.*
be more influenced by stand structure than stocking in these stands. O’Hara (1996) reached a similar conclusion with multi-aged ponderosa pine but concluded that any differences in productivity between multi-aged and even-aged stands were insignificant (O’Hara and Nagel, 2006).

The statistically significant changes in sustainability measures observed in this study indicate a lack of constancy in these plenter stands over time for all four types of sustainability indicators. These indicators provide a quantitative measure of change that was statistically significant using regression analysis; it is a judgement call as to whether this change is significant or important in any real sense. The lack of constancy may be nothing more than an intentional change in management direction/procedures or reaction to an environmental fluctuation. Zingg et al. (1997) assessed a larger group of the same plots used in this study. Their conclusions that the majority of plots had demonstrated sustainability was based, in part, on having achieved an equilibrium structure and also on an analysis that focused more on sustained yield than the broader set of sustainability measures used in this analysis. The lack of constancy in sustainability criteria reported here may be due to a number of factors. Short- or long-term climatic fluctuations could affect increment. Spiecker (1986) attributed a drop in volume increment in seven plenter plots in Germany in the late 1970s to a reduction in precipitation. Similarly, fluctuations in increment in Europe have also been attributed to N deposition (De Vries et al., 2006). Fluctuations in climate could also cause shifts in species composition such as those reported here. It is also possible that an increasingly more conservative approach to management of plenter stands in Switzerland has led to greater retention of large trees and increased stocking levels. The increase in both species diversity and species evenness also suggests a possible intentional effort to increase numbers of species and reduce the relative proportions of the most common species. Another possibility is that a change in species composition may have been the inadvertent result of a shift in opening size.

**Plenter system implications**

The plenter system is often described as an ideal system for silviculture because of its sustainability and naturalness. These results indicate that the plenter system is more of a dynamic entity than generally assumed. Although it is not clear

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**Figure 6.** Basal area outgrowth for plenter plots. Outgrowth was calculated as the basal area of trees that were missing in an inventory from a previous inventory. Each line represents the trend over time for a single plot.
if this dynamism is the result of environmental factors or management, the common perception that the plenter system assures a stable structure may be unfounded. Additionally, characterizing the plenter systems as a more natural stand structure than other systems (Larsen, 1995; Benecke, 1996) only suggests that the plenter system is as dynamic as the natural stands it may emulate. For example, Larsen (1995) described the selection system as maintaining ‘fixed structural features thereby promoting a functional steady state’. If the stand structure were maintained at some constant level, then the dynamism of the environment would prevent a functional steady state. If a functional steady state could somehow be maintained, then a variable structure over time would be required. The present plenter system represented in these plots is not maintaining a constant stand.
structure. Whether it is providing a functional steady state is beyond the scope of this study.

The target equilibrium stand structure of plenter systems (Schültz, 1975, 1997b, 2001) is the result of decades of applied research. The plenter system should be viewed as still evolving in the spirit of adaptive management. This approach may therefore explain much of the variation seen in the time-series trends in this analysis. However, it also confirms Sterba’s (2004) conclusions that more than a single equilibrium may be appropriate for multi-aged stands. There are not only differences between stands and sites but also differences over time. The strength of the plenter system may therefore be its flexibility in stands of predominantly shade tolerant species rather than its stability over time or its resemblance to natural stand structures and processes.

Figure 8. Shannon diversity index ($H'$) for richness in structure for plenter and even-aged plots. Each line represents the trend over time for a single plot.
Conclusions

Four categories of measures are presented for assessing the potential sustainability of multi-aged stand management systems and serving as criteria and indicators for general sustainability assessments. These measures include those related to (1) stocking, (2) stand increment, (3) species diversity and (4) stand structure. Maintaining these measures at constant levels should insure sustainability of multi-aged systems although some fluctuations, particularly those associated with cutting cycles, are expected.

Multi-aged stands managed with the plenter system were found to vary from the expected constancy for stocking, species diversity, increment and particularly for stand structure over the 60- to 91-year measurement periods of these long-term research plots. The majority of these plots experienced trends that significantly strayed from constancy over time. Generally, basal area increased, species richness and evenness increased, basal area increment increased and stand structural diversity increased. For plenter stands – which can be considered to be among the oldest and best-documented multi-aged silvicultural systems – this lack of constancy in these basic criteria and indicators for sustainability implies that this silvicultural system is still evolving. However, despite the lack of constancy in these sustainability indicators, the plenter system may be sustainable in a variety of forms: as an evolving system, this sustainability is not demonstrated by these data. Rather than demonstrating the strength of the plenter system, this analysis suggests a great deal of flexibility in how multi-aged stand structures are viewed and managed to achieve sustainability.

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