

Article

An Example of Uneven-Aged Forest Management for Sustainable Timber Harvesting

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Abstract: This paper presents a system of uneven-aged forest management consistent with the principles of close-to-nature silviculture with treatments adopted to the requirements of individual tree stands, depending on their development phase, growing stock volume, DBH distribution and regeneration status. The study involves an experimental forest (property of the University of Agriculture in Cracow, Poland) with an area of 455.86 ha, located in the Western Carpathians. Data about stand characteristics and development processes, including regeneration, survival and removal, were obtained by measurements conducted at 10-year intervals on 413 permanent sample plots in the years 1976–2016, resulting in a total of four measurement periods. In the first period (1976–1986), harvesting intensity was low at 2.16 m³/ha/year but subsequently increased with the development of growing stock, higher volume increments and improved age and species structure, to finally reach 10.34 m³/ha/year in 2006–2016. The mean volume of timber harvested over the entire study period was 6.12 m³/ha/year, corresponding to 65.2% of the volume increment and 2.8% of the total growing stock. Management by the close-to-nature silviculture method had a positive impact on the forest characteristics. The improved species and age structure and the increased volume increment and growing stock translated into greater stand productivity without detriment to the implementation of non-timber forest functions.

Keywords: sustainable forest management; development phase; close-to-nature silviculture; volume increment; permanent sample plot

1. Introduction

There is an increasing need to substitute fossil resources with renewable ones in order to mitigate climate change. A special role in this respect is played by sustainable timber production [1,2], in which harvesting intensity is adjusted so as to allow the forest to fulfil important ecological and social functions. This can be achieved by sustainable silviculture defined as the use of forests and forest lands in ways that maintain their biodiversity, productivity, regeneration capacity and vitality, as well as their potential to fulfil ecological, economic and social functions without damaging neighbouring ecosystems [3].

At the core of sustainability lies the simple idea that resource consumption cannot exceed resource production over time. In the short term, sustainable forest management (SFM) means that forests must be utilized in such way so as to simultaneously ensure continuous timber supply (economic value), biological diversity, resilience and resistance to disturbances (ecological value), as well as multiple non-production functions (social value) [4,5].

In multifunctional forest management of special importance are forests with diverse species and age structures [6–8] which combine the virtues of biodiversity and ecosystem sustainability with the possibility to harvest timber in ways that do not hinder the implementation of multiple

non-timber goals. Therefore, artificially planted monocultures and even-aged stands created by schematic silvicultural patterns that are managed for multifunctional forest management should be transformed into multispecies, uneven-aged stands with a fully site-adapted, highly stable species composition [9–11]. This issue primarily concerns tree stands located on more nutrient-rich sites, affording good growth conditions for mixed stands.

Economic management objectives for uneven-aged forests are generally consistent with close-to-nature silviculture (CNS), which implies that foresters should depart from the schematic application of cutting systems and embrace an individualized approach to tree stands based on the current stand and microsite conditions, drawing on the extensive body of silvicultural knowledge and experience [12–14]. This paradigm completely eliminates clear-cutting and regular shelterwood systems, while relying mostly on long-term irregular shelterwood and single-tree selection regimes. These silvicultural systems aim at tending the growing stock and improving the species composition, quality and structure of stands. While enabling efficient timber production, they also initiate natural regeneration processes and promote favourable forest development conditions. CNS is conducive to forest sustainability and imparts a natural and aesthetic appearance to stands, bringing about a diversity of their forms and stimulating highly dynamic growth processes. Even if they may appear disorderly, forests managed by CNS most effectively protect the natural environment while shaping it in beneficial ways [6,7,15].

The elimination of clear-cutting and regular shelterwood cutting over time results in more or less uneven-aged forests to which stand age categories are no longer applicable in a straightforward manner. In such situations, it seems more expedient to use the concept of stand development phases [16–19], drawing on the categories commonly used for natural forests. Development phases also apply to even-age stands resulting from regenerations in areas affected by natural disasters, biological stand degradation, or management errors.

The objectives of the present work were: (1) documenting gradual conversion of even-aged forest to more mixed uneven-aged forest; and (2) analysing the relation between the harvest volume and growing stock in four 10-year conversion periods (1976–2016).

2. Materials and Methods

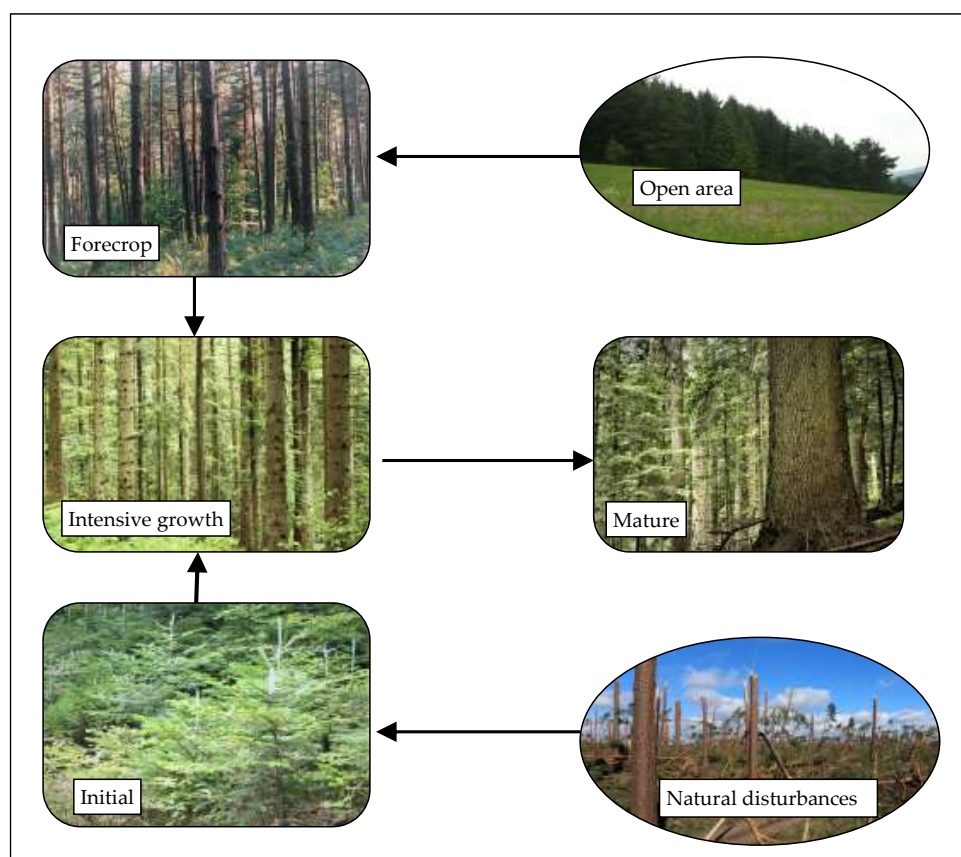
2.1. Uneven-Aged Forest Model

Between the clearly defined even-aged and all-aged forest types there exists in practice a continuity of forest forms with age structures substantially deviating from an equal distribution of stands in age classes (normal forests) and from balanced DBH structures. Tree stands of varied structures often arise from natural processes, increasing both the biodiversity and resilience of forest ecosystems [20].

A forest is deemed uneven-aged if distinct age classes cannot be identified for its stands [21,22]. While even-aged fragments may be present, they are not treated as enduring units and their age structure becomes more diverse over time. This concept of uneven-aged forests encompasses a wide variety of natural stands, from all-aged to multi-aged to single story stands with little age differentiation. In this paradigm, tree stands are not classified by age classes and so silvicultural treatments and harvesting quotas are no longer determined from the age class table. In forests exhibiting diverse structures, the metric of age becomes replaced with development phases, with the succession of the phases presented in Scheme 1.

1. The initial phase (I) corresponds to young stands with trees below the merchantable size (DBH < 7 cm). They mostly derive from natural regeneration in open areas; planted regeneration is less frequent. In uneven-aged stands managed by complex silvicultural systems with long regeneration periods (exceeding 40 years), initial phase stands are very rare, predominantly resulting from adverse events such as windthrows, fires, fungal infection, or pest damage, which effectively remove the tree layer from a given area. Uneven-aged forests may have an initiation phase that begins with small gaps.

2. The intensive growth phase (G) is characterized by a large number of stems per unit of area; most of the trees have low DBH values (7–34 cm) and intensively increase in volume. Under favourable conditions, understory regeneration may occur. In uneven-aged stands after transition period intensive growth phase occurs also rare, similar as initial phase.
3. The mature growth phase (M) describes tree stands with a considerable proportion of large older trees characterized by a volume increment that is lower than that in the intensive growth phase. Trees with a DBH of above 34 cm constitute at least 60% of the stand volume. The natural regeneration in gaps is produced.
4. The forecrop phase (F) describes stands established on non-forest areas using pioneer tree species like birch, Scots pine, grey alder and larch. The main functions of forecrop stands is creating shelter for target species such as fir and beech. Forecrop stands are considered fully transformed when the volume of target species appropriate for the site amounts to at least 70% of the overall stand volume.



Scheme 1. Succession of development phases in managed uneven-aged forests.

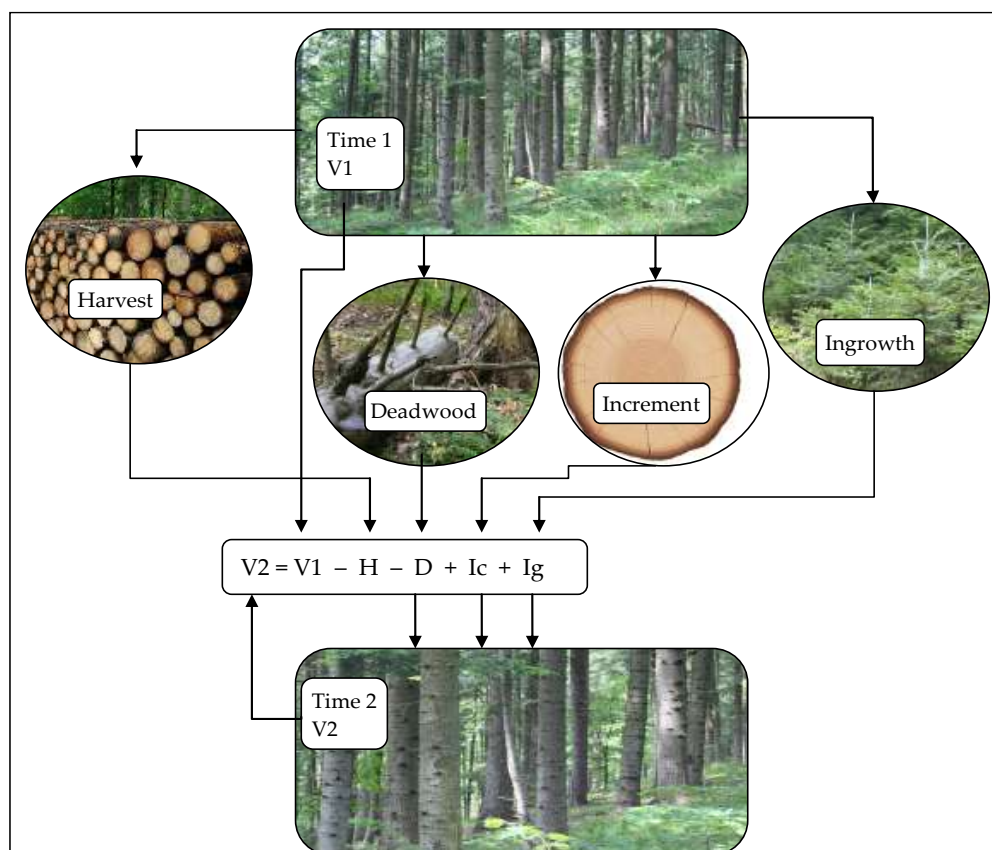
Finally, the other major structural characteristic of stands is species composition, with the three basic categories being single-species (pure), two-species and multi-species (mixed) stands.

- A stand is deemed pure if the dominant tree species accounts for at least 80% of the overall volume. Such stands are named after the prevalent species, for example, fir, beech, spruce and so forth.
- Two-species stands consist of two tree species which individually account for 30–70% of the total. Here stand names include both species in descending order of abundance, for example, fir-beech, spruce-fir and so forth.

- Multi-species stands are those in which the less abundant species jointly account for more than 20% of the stand with only one species in the 30–70% range. In this case, stand names are usually formed by preceding the prevalent species with the descriptor “mixed” (e.g., mixed fir stand).

2.2. Development Processes in Uneven-Aged Forests

Forests develop as a result of an interplay of the following three processes: regeneration, growth and removal. While in even-aged stands these processes are temporally and spatially separated depending on stand age, in uneven-aged stands they are often concurrent. Evaluation of uneven-aged stand development and management was based on the control method *sensu* Gurnaud [23,24]. In the process of growth, individual trees reach the DBH threshold (7 cm) and increase their volume by growing in height and width, advancing to consecutive DBH classes. Measures of the growth process include the volume and number of ingrowth trees (Ig) and volume increment (Ic), as is shown in Scheme 2.



Scheme 2. Development processes in managed uneven-aged forests (V1—initial volume, V2—final volume, H—volume of harvested timber; D—deadwood volume, Ic—periodic volume increment, Ig—ingrowth volume).

In the process of removal, the number of trees decreases due to natural mortality (D), adverse events and especially timber harvesting (H).

Growth and removal processes are evaluated by periodic forest inventories conducted on a network of permanent sample plots, with the results being processed by mathematical and statistical methods.

Successive measurements reveal the basic forest characteristics as well as changes in the quantity and structure of growing stock, such as species composition, mean number of stems per 1 ha, mean volume, the distribution of these characteristic by DBH class, the number of snags, the volume of downed deadwood and so forth. These measurements may also be used to assess the intensity and

direction of changes occurring in the forest directly as a result of the growth and removal processes by determining changes in growing stock volume ($V_2 - V_1$) and current volume increment (Ic) [25].

2.3. Studied Forest

The study involved the Szczawiczne experimental forest belonging to the University of Agriculture in Cracow, which is located in the Western Carpathians, Poland (47°050′–49°100′ N, 127°500′–130°100′ E). The forest has an area of 455.86 ha and ranges in elevation from 530 to 780 m above sea level, with a mean annual temperature being 5.1 °C and annual precipitation 950 mm. The studied forest is located in an area optimal for fir and beech-fir stands, with the dominant communities being *Dentario glandulosae-Fagetum* and, to a lesser extent, *Abieti-Piceetum montanum*. The main function of the forest is soil and water protection in an area abounding in natural sources of carbonated mineral water. The name of the forest “Szczawiczne” is derived from “szczawa,” a Polish word for local mineral water.

In the past, the forest was managed by the shelterwood system with a short regeneration period resulting in mostly even-aged stands. In the years 1948–1950, fields of poor agricultural value adjoining the original tree stands, many of which were not cultivated after World War II, were afforested, as were pastures situated in the immediate vicinity or within the boundaries of the existing forest. The pioneer species used for forecrop were the Scots pine (*Pinus sylvestris*) and, on wetter land, the grey alder (*Alnus incana*).

In the 1970s, close-to-nature silviculture was adopted as the management system for the experimental forest, with a network of permanent sample plots established to monitor changes in its characteristics according to the mathematical and statistical methods of forest inventorying [26,27].

The main silvicultural goal was to obtain stands with a wide variety of species compositions and age structures on the landscape level. Depending on the actual and desired stand state (a time horizon of up to several decades), the following silvicultural systems were planned for implementation: single tree selection in fir stands with a balanced DBH structure, group selection in fir stands with an unbalanced DBH structure and irregular shelterwood in forecrop stands and multi-aged stands with a significant share of light-demanding species.

The data used in this study consist of measurements from 413 sample plots located on a grid of 100 × 100 m squares, with the plot size depending on the forest development phase: 0.05 ha in mature and optimal stands, 0.04 ha in intensive growth stands and 0.025 ha in forecrop stands. The first measurements were conducted in 1976, with follow-ups in 1986, 1996, 2006 and 2016.

2.4. Measurements and Calculations

The tree layer was defined as all individuals with DBH ≥ 7 cm. The polar coordinates and DBH of all trees were measured on permanent sampling plots. DBH was measured with an accuracy of 1 mm, with the arm of the calliper always facing the centre of the sampling plot. In each sampling plot, 0.01 ha concentric circles were designated, within which the height of trees with DBH ≥ 7 was measured and rounded off to the nearest 1 m. Tree volume was calculated using volume tariffs developed on the basis of trees for which DBH and height were measured. The volume of those trees was read from tables [28]. Based on those trees, curves representing the relationship between DBH and volume were plotted for the various tree species. This relationship was used to determine the volume of the remaining trees, for which only DBH was known.

Periodic volume increment (Ic) was calculated as gross growth according to formula:

$$Ic = V_2 - V_1 + H + D - Ig \quad (1)$$

Symbols explanation as in Scheme 2. The full set of measurements as well as calculation methods was described in [29].

Detailed calculations of stand characteristics for the various measurement periods are given in the supplement.

Harvest volume is determined during forest inventories, being calculated from the sum of the volumes of individual trees designated for removal from stands due to their specific characteristics, understory regeneration and structural considerations. The maximum harvest volume for a given development phase ($H_{\max}$) is limited by the current volume increment from the previous period (V_i) using an appropriate reduction coefficient (r) representing harvesting intensity relative to that increment.

$$H_{\max} = I_c \cdot r \quad (2)$$

The reduction coefficient should be selected according to the development phase and forest conditions, in particular bearing in mind the initiation and establishment of new age classes, stand stability, as well as the desired species and age structure. It is generally thought that in the intensive growth development phase (G) the volume of selection cuts should not exceed 50% of the volume increment and so the reduction coefficient may range from 0.2 to 0.5; in the maturity phase, it ranges from 0.8 (stands with a deficiency of large trees in their DBH structure) to 1.3 (stands with a surplus of large trees and often insufficient regeneration).

3. Results

3.1. Tree Stand Characteristics

In 1976, the largest percentage share of tree stands (41%) consisted of those in the intensive growth phase, with a total area of 187.59 ha, closely followed by forecrop stands 40% (180.71 ha), while mature stands accounted for 19% (87.56 ha) of the area (Table 1).

Table 1. Tree stand characteristics in terms of species composition and development phases in 1976 and 2016.

Stand Group No.	Area (ha)	Species Composition Category ¹		Development Phase ²		Stand Volume (m ³ /ha)		Number of Trees		Species Diversity Shannon Index	
		1976	2016	1976	2016	1976	2016	1976	2016	1976	2016
1	31.2	ESF-NS	ESF mix	G	M	117	331	677	528	0.44	0.54
2	79.6	NS mix	ESF mix	G	G	171	251	697	689	0.48	0.63
3	5.95	ESF	ESF	G	M	131	449	738	677	0.27	0.39
4	18.03	SP-NS	ESF-SP	G	M	160	288	750	710	0.51	0.64
5	40.86	NS-SP	NS-ESF	G	G	140	229	630	674	0.45	0.64
6	11.95	ESF mix	SF mix	G	M	129	247	937	547	0.74	0.58
7	7.84	SP	SP mix	M	M	230	280	472	696	0.32	0.57
8	6.56	NS-ESP	NS-ESF	M	M	228	421	940	567	0.37	0.30
9	25.01	ESP	ESF	M	G	224	294	1082	608	0.31	0.30
10	17.17	SP-NS	NS mix	M	M	131	301	446	833	0.53	0.77
11	30.98	SP mix	ESF mix	M	M	174	250	655	920	0.47	0.58
12	26.96	EL-SP	EL-SP	F	F	120	360	1371	546	0.44	0.76
13	25.67	GAR mix	SP mix	F	F	99	316	1364	638	0.52	0.96
14	21.59	SP-NS	NS mix	F	F	112	195	1063	482	0.61	0.64
15	70.26	SP mix	SP mix	F	F	126	281	1260	765	0.57	0.88
16	36.23	NS-SP	SP mix	F	F	132	337	1336	676	0.57	0.79
Total/ Average 455.86		–	–	–	–	147	284	932	678	0.70	0.81

¹ EL—European larch, ESF—European silver fir, GAR—grey alder, NS—Norway spruce, SP—Scots pine, mix—mixed forest with the dominant species specified; ² F—forecrop phase, G—intensive growth phase, M—mature phase.

In subsequent follow-ups, the stands moved between the intensive growth and mature phases, except for forecrop one, all of which remained in that phase throughout the four decades. In 2016, the forest revealed the following stand composition: 40% forecrop; 32% intensive growth and 28% mature. The studied stands exhibited high species diversity. In 1976, they contained a total 16 tree species with the highest percentage share of Scots pine both in terms of volume (38.8%) and stem

number (34.3%), as can be seen from Figure 1. The second most abundant species was Norway spruce (33.4% and 32.3%, respectively) followed by European silver fir (18.3% and 11.2%, respectively). The less abundant trees (below 5% of the total volume) were grey alder and European larch, with a sporadic presence (below 1%) of beech, birch, cherry, oak, goat willow, mountain ash, sycamore, lime and aspen.

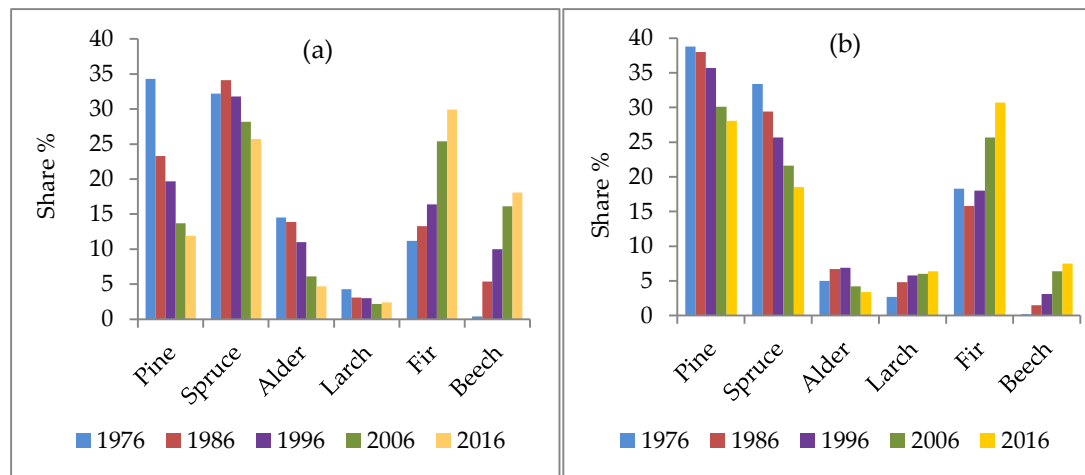


Figure 1. Percentage share of tree species by number of stems (a) and by volume (b) in the Szczawicznę forest in the years 1976–2016.

At successive measurement points, the share of target species well-adapted to the site conditions (fir, beech, sycamore, ash) was observed to increase, with declining proportions of the forecrop species (pine, alder) and spruce. In 2016, the most abundant tree species in the forest were fir (30%), pine (28%) and spruce (18%) in terms of tree volume and fir (30%), spruce (26%), beech (18%) and pine (12%) in terms of stem number. Changes of species composition category and development phase in particular stand group are given in the supplement.

The species diversity of the Szczawicznę forest as measured by the Shannon index in 1976 was 0.70 (Table 1). The lowest species diversity (0.27) was found for silver fir stands in the intensive growth development phase; they contained five species out of which fir accounted for 81% of the total, followed by spruce (15%), mountain ash (2%) and Scots pine and birch (1% each). The highest species diversity (0.74) was exhibited by mixed silver fir stands in the intensive growth phase, which consisted of seven tree species with relatively similar percentage shares. Over time, the species diversity of stands generally increased, reaching an overall value of 0.81 for the entire forest in 2016. At the stand level, the greatest improvement in diversity occurred in the forecrop stands. In 2016 the highest diversity (0.96) was found for forecrop stands with dominant alder, which contained 11 tree species.

In 1976, the mean growing stock volume was 147 m³/ha for the entire forest area, with 121, 150 and 181 m³/ha for stands in the forecrop, intensive growth and mature phases, respectively. The mean volume increment in the first measurement period (1976–1986) was 6.89 m³/ha/year for the entire forest and 9.78, 5.19 and 4.54 m³/ha/year for the forecrop, intensive growth and mature phases, respectively (Table 2).

Table 2. Ten-year stand volume increments by development phase in the Szczawicznę forest in the years 1976–2016 (in m³/ha/year).

Development Phase	1976–1986	1986–1996	1996–2006	2006–2016	Mean
Forecrop	9.78	10.52	10.70	10.71	10.43
Intensive growth	5.19	8.47	8.16	10.62	7.98
Mature	4.54	7.61	8.46	10.83	8.20
Average	6.89	9.16	9.21	10.72	8.99

The increment volume generally increased over the subsequent periods, reaching 10.71, 10.62 and 10.83 m³/ha/year for the forecrop, intensive growth and mature phases, respectively, in the 2006–2016 period.

3.2. Harvest Volume

The mean harvest volume in the first measurement period (1975–1986) was 2.16 m³/ha/year, which corresponded to 31% of the stand volume increment and 1.5% of the growing stock volume. In terms of development phases, the mean harvest volume was 1.57, 2.41 and 2.76 m³/ha/year for forecrop, intensive growth and mature stands, respectively (Table 3). In successive measurement periods the harvest volume gradually increased, reaching 4.48, 6.83 and 10.34 m³/ha/year in the 2nd, 3rd and 4th periods, respectively. Over the entire study period, the mean annual harvest volume was 6.12 m³/ha/year, which corresponds to 65.2% of the mean volume increment and 2.8% of the growing stock (Table 4).

Table 3. Harvest volume by development phase in the Szczawiczne forest in the years 1976–2016 (in m³/ha/year).

Development Phase	1976–1986	1986–1996	1996–2006	2006–2016	Mean
Forecrop	1.57	4.73	8.84	11.64	6.70
Intensive growth	2.41	4.23	5.77	9.05	5.15
Mature	2.76	4.59	3.27	11.12	7.36
Average	2.16	4.48	6.83	10.34	6.12

Table 4. Harvest volume as a percentage of volume increment and of growing stock volume by development phase in the Szczawiczne forest in the years 1976–2016.

Development Phase	1976–1986	1986–1996	1996–2006	2006–2016	Mean
	% Increment/% Growing Stock				
Forecrop	16.1/1.3	45.0/2.3	82.7/3.4	108.7/4.3	63.1/2.8
Intensive growth	46.4/1.6	50.0/2.4	70.7/2.7	85.2/3.8	61.7/2.6
Mature	60.8/1.5	60.3/2.2	38.7/1.4	102.7/3.9	86.4/2.7
Average	31.0/1.5	48.9/2.3	74.2/2.9	96.4/3.9	65.2/2.8

The lowest harvesting intensity was found for intensive growth stands and the highest for mature stands (5.15 and 7.36 m³/ha/year, corresponding to 62% and 86% of the stand volume increment, respectively).

3.3. Growing Stock Changes

The direction of changes in growing stock depended on the relationship between harvest volume and volume increment and varied between the different stand development phases (Figure 2).

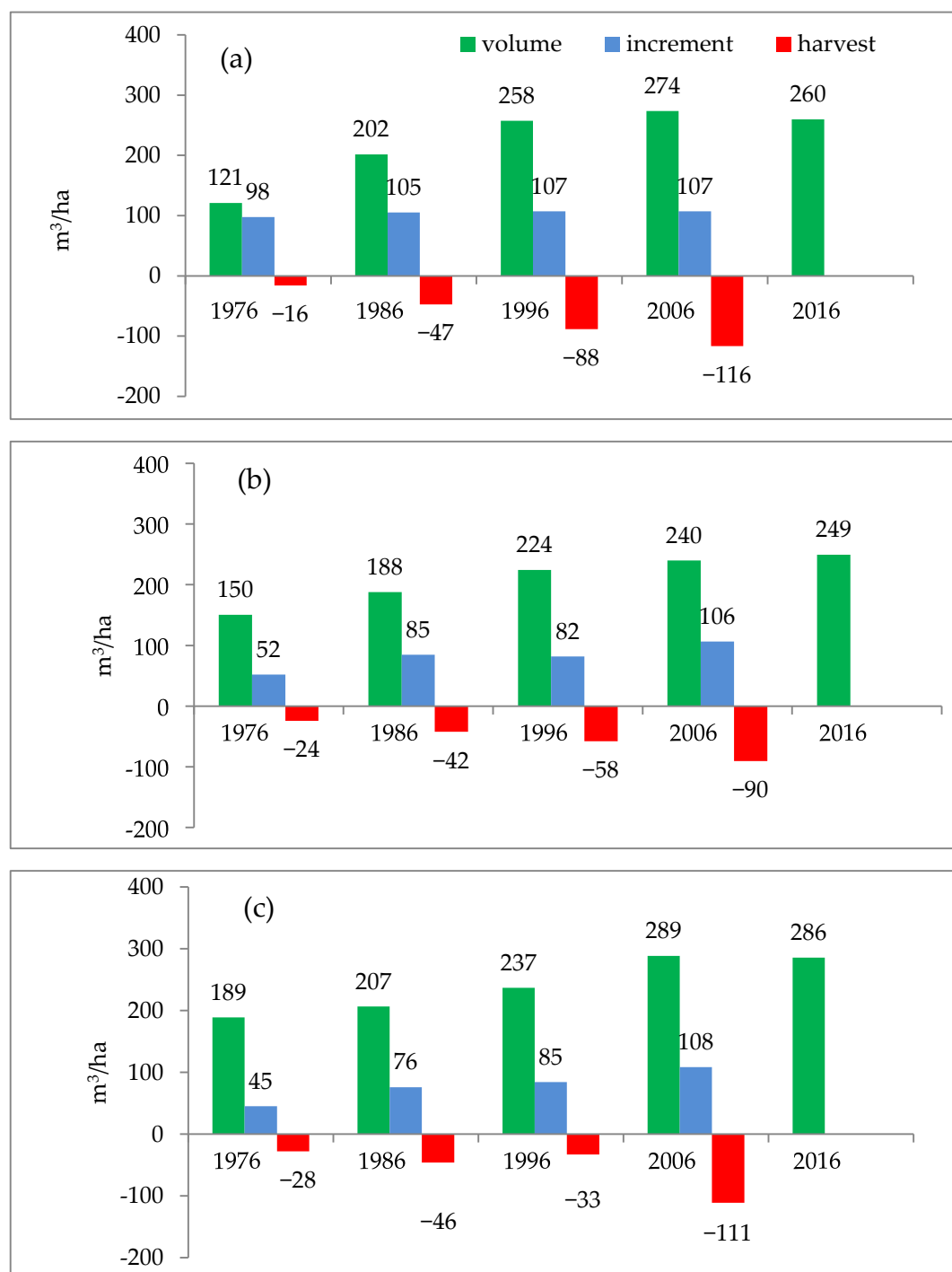


Figure 2. Relationship between harvest volume, volume increment and growing stock in the forecrop phase (a), intensive growth phase (b) and mature phase (c) in the Szczawiczne forest in the years 1976–2016.

The stands afforested in the years 1948–1950 were recorded as mostly single-species Scots pine stands in the first measurement period (1976–1986). At that time, they were approximately 30 years old and exhibited high volume increments partly due to the fact that the farmland they were planted on had been fertilized during its agricultural use. In the initial period, cutting was not very intense (16% of the volume increment) and mostly consisted of the removal of dying trees, which allowed for a substantial increase in growing stock, from 121 to 202 m^3/ha over the first 10 years. In subsequent measurement periods harvesting intensity was greater due to the introduction of a new cohort of the

target species, that is, silver fir and beech. Intensive cuts ($11.64 \text{ m}^3/\text{ha}/\text{year}$ in period 2006–2016) aimed at removing the overstory to release understory regeneration. Furthermore, in the coming two or three decades, the volume of timber harvested from the forecrop stands is likely to be quite substantial as pine trees should be for the most part removed from the tree layer, with firs and beeches being gradually recruited from the regeneration layer. However, when the forecrop stands enter the intensive growth phase, the growing stock and thus also harvesting intensity, will temporarily decrease.

Intensive growth stands were mostly subjected to crown thinnings [10] with the harvest volume being lower than volume increments in all measurement periods, which ensured a gradual increase in growing stock. The productive capacity of such stands increases over time as they move to the mature phase. Indeed, such transitions were observed in the fourth measurement period, when some intensive growth stands (57.91 ha) reached mature phase.

In mature stands the intensity of final cuts depended on the growing stock and DBH structure. In the early mature phase, intensive felling was due to the continuation of intensive shelterwood cutting within one stand (25 ha), after which the growing stock declined from 224 to $93 \text{ m}^3/\text{ha}$. However, in subsequent measurement periods harvest volumes were lower than volume increments and so the growing stock gradually recovered.

4. Discussion and Conclusions

The paper presents a forest management system in which harvesting intensity is determined on the basis of development phases rather than stand age classes. While the system is generally designed for uneven-aged forests, it may also be applied to even-aged stands which are to be transformed into more diverse structures. The case study presents well-documented changes during 40 years of transition from even-aged to uneven-aged stands.

The forest development stages described in the literature are generally derived from natural forest growth models and are typically used for characterizing unmanaged forest areas in strict nature reserves and national parks [16,30,31]. In their analysis of different approaches to life-cycle assessment methods in natural forests, Winter and Brambach [19] divided the forest life cycle into the following categories: regeneration, accelerated growth, ripening and disintegration; in addition, they observed that gaps may appear irrespective of stand phase and age. In his 1981 study, Oliver proposed four stages for describing the development of forest stands after catastrophic disturbances: stand initiation, stem-exclusion, understory reinitiation and old growth [32,33]. Large catastrophic events and processes that follow likely lead to even-aged forests, so such stages are often unsuitable for describing the development of uneven-aged forest.

The presented system does not include the degeneration phase which is greatly reduced or altogether eliminated by management treatments. The initial phase occurs rarely, mostly in the aftermath of natural disasters, while regeneration may occur in all development phases. Regeneration and its recruitment to the tree layer (reaching the 7 cm DBH threshold) is particularly important in the late intensive growth phase and in the mature phase. In areas managed in accordance with close-to-nature silvicultural principles, the forest develops through natural processes but the development phases that enhance the desirable forest functions may be promoted, while the less favourable ones may be shortened or eliminated.

O'Hara [34] emphasized that silviculture is a means to meet objectives ranging from timber production to wildlife habitat to naturalness. Rather than striving to be close to a nature that is under constant change, silviculture should strive to be better than nature. O'Hara put forward that close-to-nature silviculture may be flawed but findings from our research indicate that it leads to highly diversified forests on the stand as well as landscape levels. O'Hara stated that silviculture in the future will be highly varied and flexible. In this context, our study can be an example of management of uneven-aged forests as the combination of different silviculture methods [35,36].

In turn, Schütz [15] noted an increasing discrepancy between an economic crisis in timber production and the ecological crisis. In his opinion, it is necessary to reconcile these two poles

and find silvicultural systems which respect not only naturalness but also cost and productivity, as it is on these economic issues that the chances to succeed really depend.

The main indicator of sustainable timber harvesting is the relationship of harvesting volume to volume increment and growing stock. The control method, connected with the paradigm of sustainable forestry, provided a scientific approach to directing the harvesting process and is widely used as a management planning method for forests wherein a single tree selection system is applied [24,25,37,38]. In the presented system, harvest volume depends on the silvicultural requirements of individual stands, including their growing stock volume and is also monitored with respect to volume increments. Forest sustainability may be analysed at the level of individual stands or at higher landscape levels [39]. The relationship between harvest volume and volume increment at the stand level depends on the stand development phase. At a higher level and over a longer time perspective, forest sustainability requires that the removal processes should be balanced with the regeneration and increment processes. The former includes planned harvests as well as natural tree mortality and so the overall harvest volume at the landscape level should not exceed the volume increment less the volume of deadwood left in the forest. In the presented system, some of the trees, typically of lower economic value (e.g., forked, hollow, broken and fungus-infected) are retained to die a natural death and serve as a source of large-sized deadwood.

Carey et al. [40] developed an intentional ecosystem management strategy that can be applied to various land ownerships and, consequently, help resolve land allocation problems associated with timber supply and threatened wildlife. They concluded that regardless of the opportunities to manage for non-timber goals and community-based economic stability, if timber owners receive less return than other investments of equal risk, forest management capital may be diverted away from management for biodiversity to other, more profitable, alternatives.

Based on the case study findings, the following observations were formulated.

1. The implementation of close-to-nature silviculture improved the quality and volume of growing stock over the 40-year study period. The species composition of the stands revealed an increase in the target species of silver fir and beech and a decline in the forecrop species as well as in species not suited for mountain forest sites, such as Scots pine, Norway spruce and grey alder. The species diversity of the stands as measured with the Shannon index progressed from 0.70 in 1976 to 0.81 in 2016.
2. The stand structure and growing stock revealed a considerable improvement. Between 1976 and 2016 the mean growing stock volume almost doubled from 147 to 284 m³, while the percentage share of mature stands rose from 19% to 28% of the forest area.
3. The progress in volume increment from 6.89 to 10.72 in the years 1976–2016 resulted from favourable changes in the species and age structure of the stands as well as from the general rising trend observed in European forests in that period.
4. In the first measurement period (1976–1986) the harvesting intensity was low at 2.16 m³/ha/year and gradually increased over time with increases in growing stock volume, volume increment and the percentage share of mature phase stands, to reach 10.34 m³/ha/year in the 2006–2016 period.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2071-1050/10/9/3305/s1>. Changes of diameter distribution in stands in terms of species category and development phase are given in the supplement.

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