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Revisiting silvicultural systems: Towards a systematic and generic design of tree regeneration methods☆

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ABSTRACT

Understanding and mimicking regeneration processes in forests is crucial to sustainable forestry and forest conservation, since they largely determine the structural and ecophysiological traits as well as the ecosystem goods and services of forest stands. The techniques employed in achieving tree regeneration include the active manipulation of forest structure and are formally described by silvicultural systems. In the past, most silvicultural systems were developed locally and the corresponding authors used names and terminology that greatly varied and were often ambiguous. In addition, although local developments, silvicultural systems were often presented as "package deals" and individual components were not sufficiently defined to allow for adaptations in applications elsewhere. We critically reviewed the basic components and variants of silvicultural systems as well as their combinations in order to develop a unifying terminology that allows a better communication of regeneration methods and inspires the continued creation of new ones. Finally we applied the terminology elaborated in our review to an example of classifying silvicultural systems from Poland in order to show how existing silvicultural systems can be more clearly re-interpreted. We found that our review and analysis opened new insights on silvicultural systems that pave the way to more detailed and systematic future research in regeneration techniques. Silvicultural systems applied to high forests are often, with few modifications, also applicable to coppice forests and vice versa. Silvicultural systems also form an important element of close-to-nature or continuous cover forestry (CCF), as they contribute to diversifying forest structure by introducing new tree cohorts and the way how rigorously silvicultural systems are applied in various countries much depends on the time elapsed since the adoption of CCF.

1. Introduction

Silvicultural systems are among the early innovations that sustainable forestry came up with shortly after the first European state forest services came into existence in the 18th century (Hasel and Schwartz, 2006; Mantel, 1990). Whilst many early forestry practices mimicked agriculture, most silvicultural systems were genuinely new taking the differences between agricultural plants and trees explicitly into account. Historically, silvicultural systems even preceded the introduction of thinnings (Bauer, 1968).

In a very broad sense, a silvicultural system may be defined as the process by which stands constituting a forest are removed and replaced by new stands resulting in woodlands with distinctive structure (Troup, 1928; Matthews, 1991). Most silvicultural systems are methods of regeneration or reproduction. A regeneration method is a treatment applied to a tree community (in forestry often termed 'forest stand') and its structure with a view to establish or renew it. Each method includes the removal of all or part of the old tree community, the medium- to long-term establishment of a new one and any treatments necessary to create and maintain conditions favourable to the self-establishment and the growth of tree regeneration (Smith et al., 1997; Pommerening, 2023). In silvicultural systems, the manipulation of forest structure through human interventions plays a crucial role and is carried out so that the establishment of natural regeneration is triggered and resulting

☆ This review is dedicated to the memory of William L. 'Bill' Mason, Forest Research, UK, who passed away in June 2024.

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seedlings and saplings are sheltered from adverse environmental effects, such as frost and drought. In commercial forestry, the remaining mature trees also have the role of "nurses", i.e. they force juvenile trees to allocate more resources to height rather than diameter growth, thus achieving long, straight stems, which is a pre-requisite for good timber quality. These human manipulations of forest structure emulate the type and intensity of natural disturbances that achieve similar results but usually unfold more randomly. Since all forests eventually regenerate naturally on sites where tree vegetation dominates, the idea of silvicultural systems is to accelerate the process of natural regeneration and to optimise the outcome in terms of tree density and tree morphology by providing favourable structural, microclimatic and edaphic conditions (Smith et al., 1997). This optimisation ensures a smooth transition from one forest generation to the next. In the context of climate change and nature conservation, silvicultural systems are often preferred that avoid a sudden large-scale loss of trees and subsequent exposure of forest soil, which can give rise to carbon emissions and nutrient leaching (Ameray et al., 2021; Newton, 2007). The choice and design of silvicultural systems is one of the most crucial decisions made by a forest owner or manager because it largely determines the structural and ecophysiological traits of a forest stand as well as the tree traits responsible for the provision of ecosystem goods and services.

In modern, sustainable forestry embracing the concept of continuous cover forestry or close-to-nature forestry (CCF; Pommerening, 2023), silvicultural systems form an important part of *transformation* and *conversion* of tree plantations and monocultures to CCF. Transformation is the active, gradual change of woodland structure and/or tree species composition that eventually results in a well-structured CCF woodland, including several species and a wide range of tree sizes. By contrast, conversion is the active, abrupt change of species composition used in the context of ecosystem restoration, e.g. the conversion of non-native conifer plantations to restore native woodlands on ancient woodland sites (Spiecker et al., 2004; Vítková and Ní Dhubháin, 2013). In practice, transformation and conversion share many similarities and both require silvicultural systems for introducing the new cohorts of trees that are necessary for diversifying forest structure and for encouraging the re-colonisation of native tree species. Creating amenable conditions for the re-colonisation of native tree species and other associated vegetation follows the principles of passive restoration (Newton, 2007), i.e. the forest site is allowed to recover naturally through the process of seed dispersal, regeneration and succession as opposed to active restoration through planting or artificial seeding.

Unfortunately there is often much confusion over the terminology of silvicultural systems which is made even more difficult by different terminology standards in national languages across the world. To make matters worse, silvicultural systems were often named after regions where they were invented or after their inventors, e.g. Bavarian/Swiss irregular shelterwood system, Wagner's shelterwood system, Mortzfeldt gaps etc. Originally such descriptors attempted to express responses to local environmental conditions (Puettmann et al., 2009), but they were often meaningless or ambiguous outside the regions or countries where these names were adopted. In utter frustration, Troup (1928) wrote: "European national terminologies tend to confuse rather than to assist, since the same term is often used by different writers in a different sense, while undue importance is sometimes attached to trivial variations." Because of this confusion there is a need to develop an improved naming system based on generic principles. The names of silvicultural systems should ideally give a direct clue about what the system under consideration entails. In addition, silvicultural systems are often presented as a "package deal" and individual components are not sufficiently identified and characterised to allow for local adaptations.

The objectives of this paper are (1) to review basic and combinations of silvicultural systems with a view to identify generic principles and building blocks that apply across the world and (2) based on these, to discuss the potential for an improved communication of silvicultural systems in the scientific literature that facilitates the invention of new, combined or adapted silvicultural systems.

2. Definitions and concepts

This section presents the basic definitions and concepts of silvicultural system from a bottom-up perspective. All spatio-temporal indications are only approximate, since this is a generic review which is not specific to any particular forest ecosystem.

2.1. Basic regeneration principles

Vanselow (1949) distinguished three basic principles or situations of regenerating forest stands naturally thus describing localised stand conditions, i.e.

- shelter,
- margin or edge,
- bare land.

The *shelter principle* describes situations where trees regenerate directly under mature trees that shelter and "nurse" (see Section 1) them. The main canopy formed by mature trees is continuously opened up by repeated selective thinnings removing individual overstorey trees. As more and more of the shelter providing mature trees are removed, less protection is offered to the regeneration trees, but also resource competition between mature trees and seedlings/saplings is reduced at the same time.

The *margin* or *edge principle* applies when trees regenerate along the edge of a residual forest stand adjacent to large mature trees in small-scale open conditions which often take the shape of a strip or of a narrow zone (5–30 m). The principle is triggered wherever forest edges are created.

When trees regenerate in open conditions without mature trees nearby so that interactions between seedlings and mature trees can occur, *bare-land* conditions are given. Such conditions can exist as a consequence of large clearcuts, but they also occur in the centre of canopy gaps or strips. Naturally there is a continuous gradient between edge and bare-land conditions with a decreasing effect of residual mature trees on patches bare of large trees.

These basic building blocks are usually included in many silvicultural systems and ecological gradients between them typically exist. In the context of commercial forestry, high seedling/plant numbers are required in bare-land conditions, as no mature trees are present to influence seedling morphology in an economically positive way (see Section 1), so that only the lateral influence exerted by neighbouring seedlings contributes to economically desired tree shapes. This implies that less seedling density is required where the shelter principle is applied, as in addition to lateral (side) influences there is a vertical (overhead) effect of mature trees on seedling growth and morphology. For implementing the margin or edge principle, required seedling densities should be between those required on bare land and those necessary when following the shelter principle (Mayer, 1984). We distinguish between *basic* (Section 2.2) and *specialised* (Section 2.4) silvicultural systems. The four basic silvicultural systems are dominated by one or two of these principles. Combinations of silvicultural systems (see Section 2.3) usually include all of these principles.

2.2. Basic silvicultural systems

Mainly based on the spatial arrangement of residual mature trees in the main canopy, there are four basic silvicultural systems, i.e. *clearcut-replanting system, uniform shelterwood system, strip system* and *group system* (Fig. 1) implementing one or more of the basic regeneration principles of Section 2.1.

The clearcut-replanting system mainly implements Vanselow's bare-land principle (Section 2.1). Only in the vicinity of adjacent forest stands

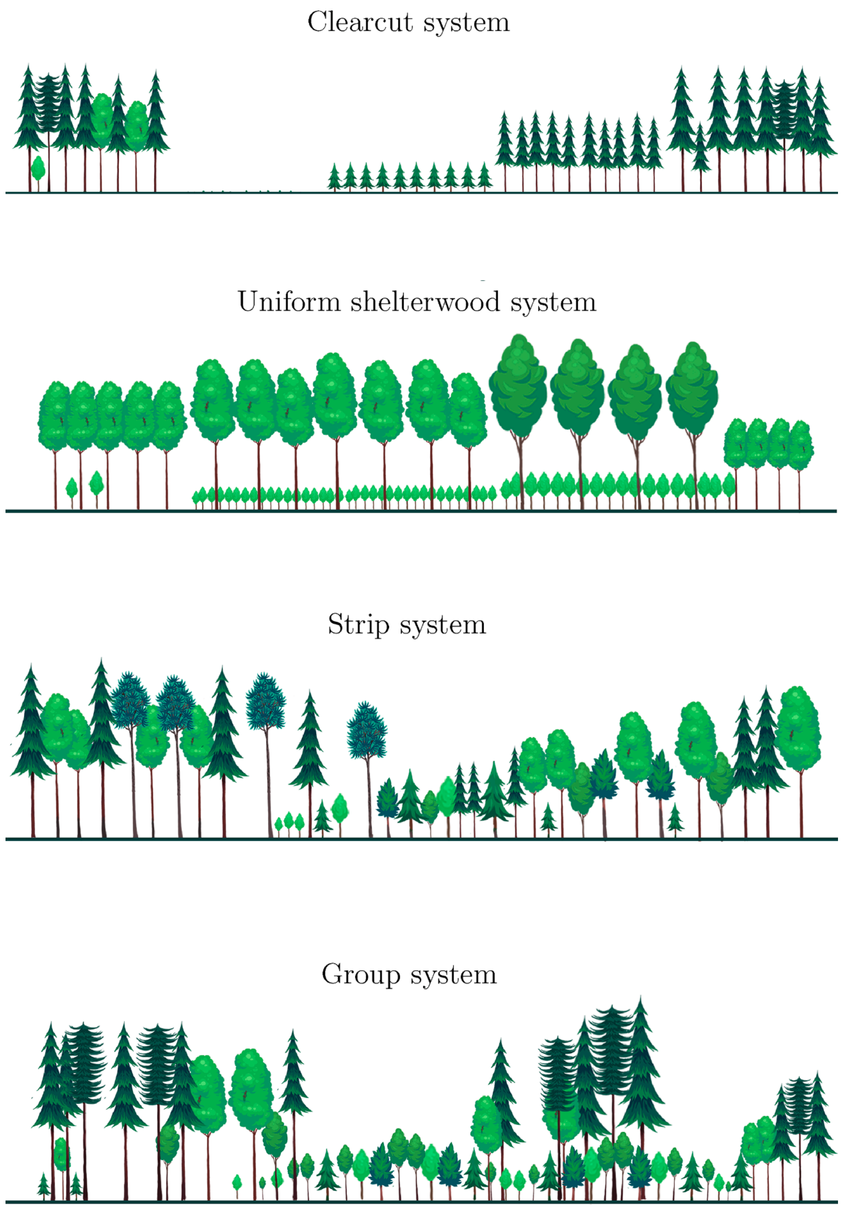

Fig. 1. Visual impression of the structure involved in basic silvicultural systems in progress. Courtesy of Zeliang Han.

the margin or edge principle is realised. The clearcut-replanting system involves a simultaneous removal of all trees of a forest stand. After a few years the area is usually re-planted using a large number of seedlings (e.g. 2500–10,000 trees per hectare). There is no protection of artificial regeneration, i.e. the replanted seedlings, by mature trees except near the boundaries and the whole stand area is affected by the intervention. Depending on species and climate, clearcutting can also be followed by natural regeneration or by a mix of natural and artificial regeneration.

As the name suggests, the uniform shelterwood system is mainly a realisation of Vanselow's shelter principle (Section 2.1). The system is achieved by repeated uniform thinnings and moderate openings of the main canopy (Fig. 1), thus removing individual trees more or less uniformly over the whole forest area. As a result, light conditions in the residual stand are uniform and all natural regeneration throughout the stand area is protected by the residual main canopy for some time. The cuttings of mature trees affect the whole stand area. The uniform shelterwood system is one of the oldest silvicultural systems dating back at least to the 18th century (G. L. Hartig) when it was primarily designed for regenerating *Fagus sylvatica* L. in Central Europe, but most likely is much older (Troup, 1928). For light demanding tree species the overstorey needs to be opened more than for light and intermediate species. For a limited time, two storeys are present in the forest, i.e. the mature overstorey and the new cohort of regeneration trees in the understorey. Eventually, the remaining overstorey trees are removed in the last secondary fellings, i.e. in the removal fellings (see Section 2.3), in 3–6 interventions over 15–30 years depending on species composition, understorey requirements and management objectives (Matthews, 1991; Smith et al., 1997; Nyland, 2002).

The strip system largely implements the margin or edge principle defined by Vanselow (1949; Section 2.1), however, in most applications of this system there is also an element of the shelter principle inside the yet uncut forest stand and immediately adjacent to the strip (see Section 3). Naturally, the gradient in ecological conditions is much steeper at edges than in a uniform shelterwood system. If the strips are wide (for example, in excess of 30 m), the bare-land principle can also apply. Köstler (1956; in the translation by Mark L. Anderson) refers to this system as the *marginal system*. The strip system involves a simultaneous removal of all trees in comparatively narrow, parallel strips. Strip width usually is 1–2 (max. 3) total tree lengths, i.e. approximately 30 m on average, although also narrow strips (5–20 m) have been used (Wagner, 1912; Kautz, 1921, 1922). Particularly when mainly concerned with species susceptible to windthrow, progressive strips are cut perpendicular to the main wind direction and strip cutting progresses from the direction opposite of the main wind direction towards the wind. Alternatively, the cuttings progress towards the direction of midday sun (i.e. from north to south) so that the upcoming new stand is protected from high temperatures. On slopes, strips would progress downhill from the top to the bottom. Depending on local environmental conditions other strip alignments have been successfully applied (Troup, 1928; Smith et al., 1997). Subsequent strips are cut 5–20 years after the most recent strip was cut until the whole area is eventually regenerated (Rittershofer, 1999). Regeneration trees on the strips mostly benefit from lateral protection by mature trees, particularly near the edge of the residual forest stand. There is also a limited amount of vertical (overhead) protection approximately one tree length from the edge inside the residual forest stand. The cuttings of mature trees are strictly localised. The successor stands are uniformly structured in strip direction (i.e. parallel to the regeneration frontiers) and approximately of the same age, whilst the juvenile trees have size differences and are uneven-aged in the direction of strip progression (Fig. 1). The strip system is a relatively recent development and was formalised at the beginning of the 20th century, although precursors apparently date back to the 18th century (Troup, 1928). Important protagonists include Eberhard, Philip and Wagner (Vanselow, 1949) and the strip system is also considered a comparatively rapid regeneration method (Matthews, 1991).

The group system is a realisation of two principles proposed by Vanselow (1949), i.e. the bare-land and the margin or edge principle. This silvicultural system involves the cutting of regularly or irregularly shaped canopy gaps that can vary in size. The gap cutting is usually staggered in time. In the centre of large gaps, the bare-land principle is realised whilst along the peripheries of the canopy gaps there is a realisation of the margin or edge principle (Fig. 1). In small gaps, only the margin or edge principle takes effect. The cuttings of mature trees are strictly localised, they only occur in or near the gaps. The group system was first formalised by Gayer (1886) with the explicit objective to regenerate mixed-species forest stands (Mantel, 1990). Ideally, the crown canopy is opened only where advance regeneration is in place or where the likelihood of imminent seed germination in sufficient numbers is very high. The resulting gaps create a range of microclimates and light regimes suitable for tree species with different environmental requirements. Ecologically group systems are close to regeneration processes in natural European forests of the temperate zone involving small disturbance patches.

In their most simple application both strip and group system can be described as systems where the mature trees to be removed are clustered according to different geometric principles. Another way to describe simple strip and group systems is to argue that they are miniature clearcuts that are limited to a small subset of the whole forest stand. The uniform shelterwood system and the strip system are considered comparatively safe options when forest stands are exposed and tend to be prone to windthrow (Troup, 1928). This assumes that the most resilient trees form a long-term overstorey of the uniform shelterwood system and are not overcut. In exposed situations, the group system is often considered risky since the gaps can give rise to wind turbulences (Burschel and Huss, 1997). Light-demanding species can be more easily regenerated in canopy gaps and on strips. From a logistic point of view (harvesting and stem extraction technology), the strip system is easiest to carry out followed by the uniform shelterwood system and lastly by the group system. In situations where shelterwood cuts are not applied uniformly but in an irregular way involving variable densities of residual overstorey trees, the resulting forest structure can sometimes be similar to early stages of the group system (Matthews, 1991). Refined applications of the group system also require more silvicultural and ecological skills than those of the other two systems (Pommerening, 2023). All of these methods can be used for regenerating both single-species and mixed-species forests.

2.3. Tree felling terminology

In the majority of cases, complete natural regeneration does not follow from a single felling and the protective cover for the seedlings may be necessary to maintain for some years after they appear. Thus the mature trees are not removed by a single felling but by several successive fellings. Most silvicultural systems therefore include a set of successive regeneration fellings (Troup, 1928). For describing the interventions into the main tree canopy a standard set of terms has evolved that applies more or less across the whole range of regeneration systems with the notable exception of the clearcut and the specialised systems (Section 2.4; Matthews, 1991):

Preparatory fellings/cuts. Essentially thinnings with the objective to uniformly reduce the density of the main overstorey so that individual-tree resilience is fostered whilst seed production is stimulated. Tree selection does not follow the specific spatial pattern of the silvicultural system.

Regeneration fellings/cuts. Beginning with the seeding and ending when the final felling has been carried out and the young stand is fully established. Tree selection follows the spatial pattern of the silvicultural system.

> *Seeding (establishment) fellings/cuts*. Intervention to encourage and initiate seed production and dispersal whilst maintaining the woodland climate necessary for germination and seedling growth.
>
> *Secondary fellings/cuts.* Intervention to successively remove the overstorey and uncover the regeneration as to provide more light, water and nutrients.
>
> *Final or removal fellings/cuts.* The last of secondary fellings. All remaining overstorey trees are removed, and the fully established regeneration remains.

Preparatory fellings typically prepare the overstorey trees for seed production and, as part of this, foster individual-tree resilience so that the increasingly sparser main canopy can continue to sustain wind and snow. Preparatory fellings do not follow the spatial pattern of the regeneration pattern, e.g. strips or groups. Uniform shelterwood cuts, for example, are often used as preparatory fellings regardless of the basic silvicultural system selected (Mayer, 1984). Preparatory fellings are often not necessary, if the stand in question has had a good thinning history with regular, not too weak interventions in the past so that the crowns of the overstorey trees are well developed and small gaps between adjacent crowns exist. In that case, advance regeneration has often already started to colonise the forest floor. The regeneration fellings typically follow the spatial pattern of the basic silvicultural system selected, i.e. uniform removal or gap, strip alignments (Pommerening, 2023). Several seeding fellings are usually carried out in order to take advantage of several good seed years, for fostering resilience but also for supporting structural irregularity. The number of removal fellings depends on environmental and logistic conditions. They may take between 5 and 20 years at temporal intervals between 3 and 6 years. Generally, on dryer and nutrient-poor soils removal fellings are fewer and proceed at a faster pace than on wet sites. If initial regeneration is sparse or if the species to be regenerated is frost tender, it may be necessary to prolong the retention of the overstorey. For the sake of preserving soil and microclimatic conditions it is helpful to spread the final overstorey removal over several interventions (Mayer, 1984; Burschel and Huss, 1997).

2.4. Specialised silvicultural systems

In the Anglo-American literature, the impression is often conveyed that silvicultural systems are treatment programmes defining the development and progression of a tree community or forest stand indefinitely (Matthews, 1991; Smith et al., 1997; Nyland, 2002). For example, in the IUFRO terminology of forest management, Nieuwenhuis (2000) defined silvicultural systems as 'planned programmes of treatments extending throughout the life of forest stands that include harvesting, regeneration and tending methods or phases. They cover all activities for the entire lifetime of a forest stand'. A very similar definition can be found in Smith et al. (1997). By contrast, the Central European school of silviculture clearly sees silvicultural systems mainly as broad regeneration methods that are applied for a comparatively short time of a forest's total lifetime (Burschel and Huss, 1997; Rittershofer, 1999; Bartsch et al., 2020), because once the regeneration process is complete the silvicultural system is finalised as well. After that, other treatments (usually thinnings) that are not related to the finalised silvicultural system need to be determined for the future of the new forest generation until the regeneration process is initiated again towards the end of the lifetime of this forest generation. There are two notable exceptions from the Central European view, i.e. the *selection* (*plenter*) *system* and the *two-storeyed high forest* (Fig. 2).

These two silvicultural systems are not regeneration methods *per se*, but rather wholesome treatment programmes in the Anglo-American sense of silvicultural systems and we therefore consider them to be *specialised silvicultural systems*.

2.4.1. Selection (plenter) system

Originally invented by farmers with small, upland forest ownerships, the single-tree selection system is characterised by the fact that all tree sizes and development stages are present and intimately mixed in a single forest stand. All forest operations simultaneously affect all of these stages (Rittershofer, 1999; Andrzejczyk 2006; Drozdowski 2022; Pommerening, 2023), although interventions are always local and never global, i.e. they are never schematic across the whole stand area. Historically there is circumstantial evidence that the selection system may have gradually evolved from coppice with standards (see Section 2.6; Schütz, 2001). Schütz (2001) pointed out that a forest stand managed according to the selection system includes trees whose crowns do not touch, but have a tendency to occupy the entire vertical growing space (cf. Fig. 2, top). The most common intervention is the felling of few individual, mostly large trees at fairly short but irregular thinning cycles. In these interventions, no interruption in the main canopy should be larger than the extent of one dominant tree crown. Subsequently, regeneration spreads throughout the stand and occurs simultaneously with other development stages (Burschel and Huss, 1997; Schütz, 2001). Large trees removed are rapidly replaced by mid-storey trees which in turn are supplemented by regeneration trees in the understorey. The system can be thought of as a kind of *process conservation*, where an old-growth forest is permanently kept in a disturbance and regeneration phase. Unlike the situation when applying basic silvicultural systems (Section 2.1) and their combinations, selection forests have no distinct forest generations and they ensure the self-sustainability of size structure at stand level (Pommerening, 2023). The application of the selection system requires experienced and highly skilled forestry staff.

2.4.2. Two-storeyed high forest

A two-storeyed high forest is composed of an upper and a lower storey of trees, growing in intimate mixture on the same site (Matthews, 1991). In contrast to the uniform shelterwood system, where two or more canopy storeys *temporarily* co-exist with the mature overstorey until it is finally removed (see Section 2.2), in two-storeyed high forests two distinct canopy strata are maintained more or less on a *permanent* basis (Fig. 2, bottom). Each storey usually is comparatively homogeneous in terms of species composition, tree size and age, but these characteristics differ markedly between the two storeys. It is important to keep the understorey trees in a stand-by position so that they can just survive but do not emerge into the mid- and overstorey prematurely (Burschel and Huss, 1997; Pommerening, 2023). In the long term, the overstorey is replaced by the understorey and a new understorey needs to be initiated, usually through natural regeneration but underplanting is also possible (Bauer, 1968). Two-storeyed high forests are comparatively rare. A prominent example exists at the Schlägl estate in Austria (Reininger, 2001). The two-storeyed high forest can also serve as a transitional phase during the transformation of a plantation to a selection forest (Sterba and Zingg, 2001). The application of the system is easier than that of the selection system whilst sharing some of its advantages and structural complexity (Matthews, 1991).

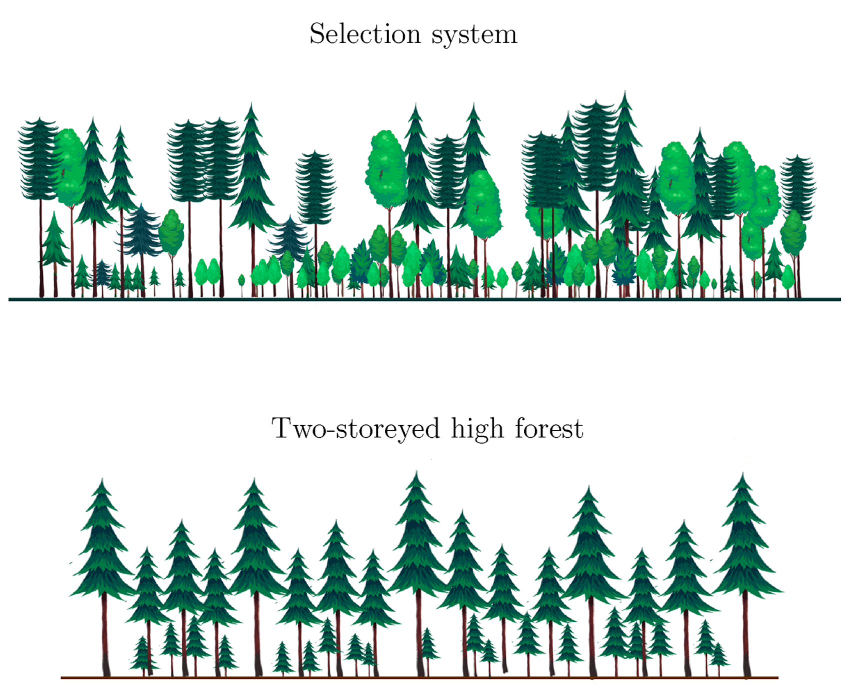

Fig. 2. Visual impression of the structure involved in specialised silvicultural systems, i.e. the selection system and the two-storeyed high forest. Courtesy of Zeliang Han.

Table 1
Overview of the variants of (basic) silvicultural system.

Silvicultural system	Variant
Any system	- Mixing natural and artificial regeneration - Groups, strips etc. can be man-made (cuttings) or of natural origin (small-scaled disturbance)
Clearcut system	- Planting (artificial regeneration) - Natural regeneration - Preference of small to medium-sized clearcut areas - Seed trees, standards (retention)
Uniform shelterwood system	- Seed trees, standards (retention)
Strip system	- Alternating strips - Inner strip only - Inner + outer strip - Regular, irregular strip shape including indentations - Wedges instead of strips
Group system	- Simple static gaps (Mortzfeldt) - Regular (chequerboard) dispersion of alternating gaps - Irregular dispersion of gaps - Adapting, dynamic gaps: concentric, crescentic - Circular gaps - Irregular gap shapes including ellipses - Simultaneous gap cutting - Staggering gap cutting in time - Irregular shelterwood system - Inclusion of natural gaps (from disturbances)
Selection system	- Single-tree selection system - Group selection system - Irregular shelterwood system - Anderson group selection system - Monospecific selection system

2.5. *Variants and combinations*

Basic silvicultural systems as described in Section 2.2 are hardly applied in the field in isolation, although this would theoretically make applications easier (Troup, 1928). For successful applications, basic and specialised silvicultural systems always need to be adapted to local environmental conditions. This adaptation is often achieved by *variants* and *combinations* of silvicultural systems implemented in the same area. Variants are first steps of an adaptation towards environmental or logistic requirements and include comparatively small variations of one and the same basic silvicultural system (see Section 3 and Table 1). Combinations are more fundamental variations, involve the merging of the techniques of two or more basic or specialised silvicultural systems, and as a consequence are typically more flexible in practical applications, however, they are harder to implement than basic systems (see Section 4 and Table 2). The components of combinations provide synergy effects whilst diminishing the disadvantages of the basic systems when implemented in isolation. Combinations of silvicultural systems merge two or more silvicultural systems either *spatially* or *temporally* (Vanselow, 1949). Spatial (or additive) combinations are executed at the same time but in different parts of the forest stand. Temporal (or substitutive) combinations are implemented in the same parts of the forest stand but at different times. At some level, the differences between variants and combinations are fluid. Variants of silvicultural systems often do not have particular names whilst combinations usually have distinctive names.

2.6. *High forest and coppice (low) forest*

The terms *high forest* and *coppice* or *low forest* describe fundamental silvicultural regimes (Köstler, 1956) operating at a higher level than silvicultural systems. High forest applies to forest stands that mainly include trees resulting from sexual reproduction and were grown from seeds. Such stands typically reach heights that are consistent with the potential for the given species and environmental conditions. By contrast, trees in low or coppice forests predominantly reproduce vegetatively from dormant, adventitious buds on tree stumps. low-lying branches or roots near the soil surface. There is also a combination of both regimes, which is referred to as *coppice with standards* involving a coppice understorey and an overstorey grown from sexually reproduced trees (Troup, 1928). Most of the silvicultural systems discussed in this review were originally proposed for high forests but many of them are applicable to or share similarities with coppice-forest silvicultural systems. For example, clearcutting (Section 2.2) and replanting is similar to basic coppicing, i.e. felling all trees and allowing them to re-grow from stumps. The uniform shelterwood system (Section 2.2) and the two-storeyed high forest (Section 2.4.2) share similarities with coppice with standards. Coppice variants of single-tree selection forests (Section 2.4.1) also exist, e.g. in Ticino (Switzerland) where they have a long tradition. There is also a theory suggesting that many high forest silvicultural systems had precursors in coppice management (Mantel, 1990; Hasel and Schwartz, 2006).

3. Variants of silvicultural systems

As indicated in Section 2.5, variants of silvicultural systems offer important strategies for diversifying and adapting basic silvicultural systems to specific environmental and other requirements. They usually only involve small variations that are fairly easy to implement.

Variants of silvicultural systems start with the choice of regeneration, i.e. natural or artificial regeneration (Table 1). Even in the context of CCF it is not necessary and sometimes even not desirable to regenerate forest stands naturally to a 100%. As part of conversion it may be necessary to introduce a species change or to achieve a mixed-species forest by partial planting. However, it can also happen that no natural regeneration occurs on larger patches of a forest stand within a given time and then it can be necessary to plant seedlings of the same species as those expected to regenerate naturally to compensate for the lack of natural regeneration. In the case of partial planting, comparatively wide spacings are possible, since the planted seedlings are laterally and/or vertically protected by other seedlings or mature trees (see Section 1; Pommerening, 2023). Such localised planting is naturally much cheaper than a full replanting of the whole stand area after clearcutting, since considerably less plants are required (Mayer, 1984). Mixing natural and artificial regeneration is possible with all silvicultural systems, even with the clearcut system.

The clearcut system is usually associated with replanting, but there are examples in many countries, e.g. in *Pinus sylvestris* L. in Poland, in *Picea sitchensis* (Bong.) Carr. in Ireland and in *Pinus pinaster* Aiton in Spain, where clearcutting is followed by natural regeneration. Another variant of the clearcut system is the use of retention trees (seed trees or so-called standards/reserves) where 5–15% of mature trees or 5–15

Table 2
Overview of the principle combinations of (basic) silvicultural system.

Name	Component	Description
Compartmentalised silvicultural systems	Basic silvicultural system + zones (strips)	Basic silvicultural system progressing in zones
Shelterwood inside systems	Shelterwood in cutting areas (gaps, strips)	Shelterwood components in gaps or strips
Shelterwood outside systems	Shelterwood outside cutting areas (gaps, strips)	Gap or strip cuttings combined with a uniform shelterwood system outside the gaps/strips in the residual stand matrix
Group-strip system	Group + strip	Combination of group and strip system

trees per hectare, either uniformly dispersed or in groups, are spared in the clearcutting. The role of seed trees is to provide seed dispersal for the establishment of natural regeneration whilst the purpose of standards or reserves is mostly for conservation to retain a minimum of tree cover, micro-habitats and soil protection. Both methods are often referred to as seed-tree system or retention system (Ezquerro et al., 2019). In most cases, the retained trees are left on site until they naturally die and turn into deadwood, some, however, are harvested at a later stage after putting on much increment. The strip system has also often been interpreted as a small-scaled variant of the clearcut system (Burschel and Huss, 1997).

From a theoretical point of view, both seed tree and retention systems also form a variant of the uniform shelterwood system which can be achieved by continued, uniform thinnings in the overstorey. Depending on the density of the residual trees, either a classic uniform shelterwood system results or a low-density seed tree/retention system, i.e. both systems operate on a continuous gradient of residual tree density.

A strip variant with a long tradition and curious military roots going as far back as 1761 is the *alternate clear-strip system* (Table 1). In its usual form the alternate clear-strip system includes clearcutting parallel strips through the forest, usually up to 30 m wide, leaving intervening untouched belts of equal width between these strips thus scattering seeds into two directions. The clearcut strips are regenerated artificially or naturally, and the upcoming seedlings benefit from the lateral protection of these belts. When the young cohorts on the regenerated strips are fully established and out of danger from frost or drought, the intervening belts are felled and regenerated artificially. This method was later improved by increasing the width of the clearcut strips to 40–50 m whilst reducing the width of the belts of untouched forest to 15–20 m (Troup, 1928). The alternate clear-strip system can, of course, be modified by using shelterwood components rather clearcutting whole strips, which would then qualify as a combined system, the *alternate strip shelterwood system* (Köstler, 1956).

Another simple variant of the strip system relates to the question whether the method is limited to cutting a simple *outer strip* or whether an *inner strip* is also provided (Wagner, 1912). The outer strip is the actual, 15–30-m wide strip (half to one local tree length) where all trees are removed. The inner strip is another strip immediately adjacent to the outer strip but inside the intact forest stand (Fig. 3A). Here a uniform thinning in the overstorey is performed (seeding felling, see Section 2.3) in order to encourage natural regeneration (Bartsch, 2020).

The seedlings in the inner strip receive vertical (overhead) as well as lateral (side) protection while the seedlings in the outer strip obtain lateral protection only (Troup, 1928). Inner and outer strips do not need to have the same width. For example, in Polish forest practice, the inner strip is often wider than the outer strip, a similar example is also given by Vanselow (1949). Other variants relate to the shape of the strips where irregular shapes and particularly wave-like indentations (*bay fellings*) are encouraged in most countries (Vanselow, 1949). In practice, irregularly shaped strips often follow contour lines, forest roads, water courses, rock formations or other geographic features (Troup, 1928). Wagner (1912) proposed *step fellings* where the strips advance diagonally in a stepwise pattern in a more or less south-westerly direction. All these approaches are often aesthetically more appealing than straight lines and enlarge the regeneration frontier. Such a tendency is even maximised in the so-called *wedge system*, as devised around 1920 by Eberhard and Philipp in the Black Forest (Germany), where straight frontier lines were completely abandoned in favour of a system of comparatively steep wedges operating at an angle towards the main wind direction (Fig. 3B; Mathews, 1991). The wedge system is said to be even more windfirm than the standard strip system whilst potentially increasing tree species diversity.

The most simple variant of the group system is cutting *static* canopy gaps of a certain size that remain fixed and do not expand (Table 1). This method has been first proposed by Mortzfeldt (1896) in the context of forest restoration and was also referred to as 'canopy-hole cutting'. In North-Eastern Germany (now Poland and Russia), Mortzfeldt cut such gaps in mono-species *Pinus sylvestris* forests and planted *Quercus* spp. seedlings in them, but the method has also been tried for diversifying lowland *Fagus sylvatica* forests (Ceitel and Perz, 2006; Bartsch, 2020) and mountain conifer forests with light-demanding broadleaves (Mosandl, 1984). In analogy to the alternate strip system it is also theoretically possible to include the concept of static canopy gaps in an alternate patch or even a chequerboard system (Franklin and Forman, 1987; Nyland, 2002), although this system has not been very successful due to catastrophic windthrow. More common and more flexible is the use of *dynamic*, expanding gaps. Such gaps are enlarged in every intervention to keep up with the regeneration progress and for concentrating regeneration in certain cardinal directions where prolific environmental

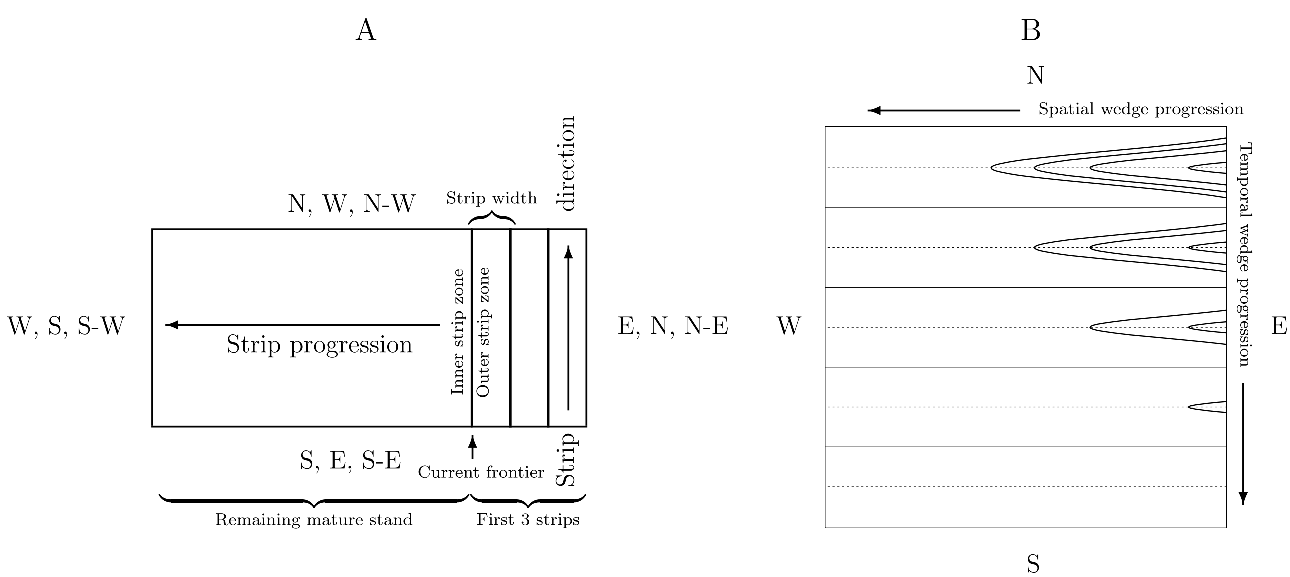

Fig. 3. A: Schematic overview of a basic strip system with the first three strips already cut. The capital letters give common alignments of strips and strip progression in the Northern Hemisphere. Adapted from Pommerening (2023). B: Schematic example of a wedge system with a spatial orientation towards west and temporal progression in southern direction. The nested wedge lines indicate successive tree-cutting frontiers in time from east to west. Dashed straight lines give the direction of wedge cutting progress and continuous straight lines indicate extraction racks. Adapted from Pommerening (2023).

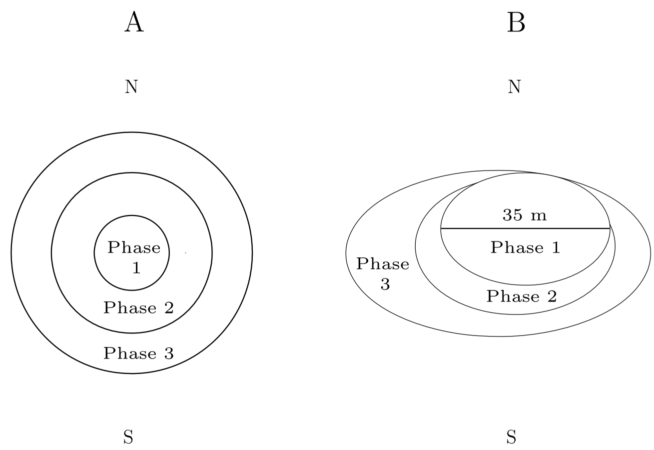

Fig. 4. A: Schematic representation of concentric spatio-temporal gap enlargements in a group system. B: Schematic representation of a crescentic spatio-temporal gap enlargement in a group system including the differences in microclimatic zones in the Northern Hemisphere.

conditions prevail. Gap enlargement shares similarities with the strip system, since the enlargement zones are essentially narrow strips. Gap enlargement can have two purposes (1) to release advance regeneration at the gap periphery by removing more or less all mature trees and (2) to encourage natural regeneration beyond the release zone by shelterwood-like selective removals of mature trees in narrow rings adjacent to the gap (Troup, 1928; Burschel and Huss, 1997; Drozdowski, 2018). Gap enlargement can be achieved in a *concentric* (Fig. 4A; Vanselow, 1949; Joyce et al., 1998) or in a *crescentic* way (Fig. 4B) that Vanselow (1949) referred to as *eccentric*. Following the concentric strategy, a ring or doughnut at the periphery of the gap is cut, i.e. the new outer rings have the same width in all directions.

Though possible, from an ecological point of view this is often not considered a wise strategy, since distinct ecological zones exist in canopy gaps and species composition as well as regeneration progress differ in cardinal directions (Bartsch, 2020; Burschel and Huss, 1997; Smith et al., 1997). For example, in the Northern Hemisphere the south and south-western parts of canopy gaps usually offer much better conditions than the north and north-eastern patches (Fig. 4B). That is why crescentic canopy enlargements are usually preferred in group systems. Gradually expanded gaps eventually coalesce and thus with time the whole stand is more or less regenerated. Although static and dynamic canopy gaps are usually applied separately in different stands, it is theoretically also possible to mix them as part of one and the same silvicultural system.

Experience and research in mountain forestry have revealed that other gap shapes such as ellipses better elaborate ideal seedling habitats and do not trigger avalanches at the same time (Streit et al., 2009). Another variant of the group system is the *irregular shelterwood system*. This system is often said to be a combination of group system and selection system with long, almost indefinite regeneration periods. There is a clear absence of zones or compartments (see Section 4.1) in this system, i.e. regeneration can be initiated and released anywhere in a forest stand, and there is no particular direction of regeneration or felling progress. This flexible and fluid management probably is the most important characteristic of the irregular shelterwood system, which dominates forest management in Switzerland (Leibundgut, 1966; Twaróg, 2003; Drozdowski, 2018). The irregular shelterwood system is not sharply defined in the literature and more than any other silvicultural system means different things to different people (Troup, 1928; Szymański, 1992). The irregular shelterwood method is closer to the specialised silvicultural systems (see Section 2.4) which are designed as long-term management programmes (Rittershofer, 1999; Schütz, 2001) and require skilled staff.

As part of both the strip and the group system, it is possible to partially or entirely rely on gaps caused by natural disturbances, e.g. wind, fire and bark beetles. This variant of basic silvicultural systems offers the opportunity to actively include natural disturbances in the regeneration process (Table 1).

The irregular shelterwood system can also be considered a variant of the selection system. Traditionally implemented as single-tree selection system, other variants include the group selection system, where groups of 2–3 mature trees are removed in interventions and the Anderson group selection system (Wilson et al., 1999; Kerr et al., 2010). The latter is an application of the normal forest idea to canopy-gap cutting in single stands. Traditional selection systems usually included three species, i.e. *Picea abies* (L.) Karst., *Abies alba* Mill. and *Fagus sylvatica*, but outside the traditional area of selection forests in Europe successful applications of monospecific selection forests have been reported, mostly with *Picea abies* (Petersen and Guericke, 2004; Olofsson et al., 2023), *Fagus sylvatica* (Schütz, 2006), *Pseudotsuga menziesii* (Mirb.) Franco (Schütz and Pommerening, 2013) and with *Pinus sylvestris* (Barzdajn et al., 1993; Barzdajn and Zientarski, 2007; Andrzejczyk 2006; Czachorowski and Drozdowski 2021).

4. Combinations of silvicultural systems

This section defines and describes fundamental types of combinations of silvicultural as they occur in the literature and suggests appropriate new terminology where required.

4.1. Progressive or compartmentalised silvicultural systems

It is possible to implement silvicultural systems progressively in small areas or *zones* rather than simultaneously across the whole forest stand (Table 2). In fact, silvicultural systems are often implemented in such a way that they do not affect the whole stand area at once. For that purpose, particularly large stands are subdivided into progress zones and the cuttings gradually proceed in these zones into the main wind direction. Troup (1928) and Pommerening (2023) referred to this combination as *progressive* silvicultural systems, but *compartmentalised* silvicultural systems may perhaps be a more explanatory descriptor. The zones or compartments of progress usually are strip-like areas and the literature occasionally interpreted them therefore as combinations of clearcut, uniform shelterwood or group system on one hand and the strip system on the other (Bartsch et al., 2020), which led to much confusion. However, the zones or compartments of progress can theoretically have any shape and width and depend on environmental factors. Therefore it is also possible to argue that compartmentalised silvicultural systems are simply variants of non-compartmentalised silvicultural systems. Zones are usually rather large, whilst strips hardly exceed widths of 30 m on average. Troup (1928) and Smith et al. (1997) used the term *cutting section* for zone or compartment.

Particularly the group system is known to operate in progress zones with a width of approximately 100–150 m towards the main wind direction (Fig. 5), but the uniform shelterwood system has also often been used in this way. A uniform shelterwood system can, for example, be limited to zones of 50–100 m which progress every 5–15 years. As always in modern silviculture, the width of zones and the progression pace depend on the dynamics of regeneration, other environmental factors and logistic conditions as opposed to a scheme of rigidly fixed intervals between successive fellings (Troup, 1928).

Clearcutting executed in progress zones is also common and largely results in the strip system. Compartmentalised silvicultural systems potentially lead to more diverse forest structure as a result of achieving different regeneration cohorts and tend to operate at a faster pace than their basic counterparts (Burschel and Huss, 1997). The use of zones or compartments does not imply that the regeneration in one zone has to be complete throughout before the next one can be worked on. As shown in Fig. 5, it is rather common to revisit previous zones whilst working in a

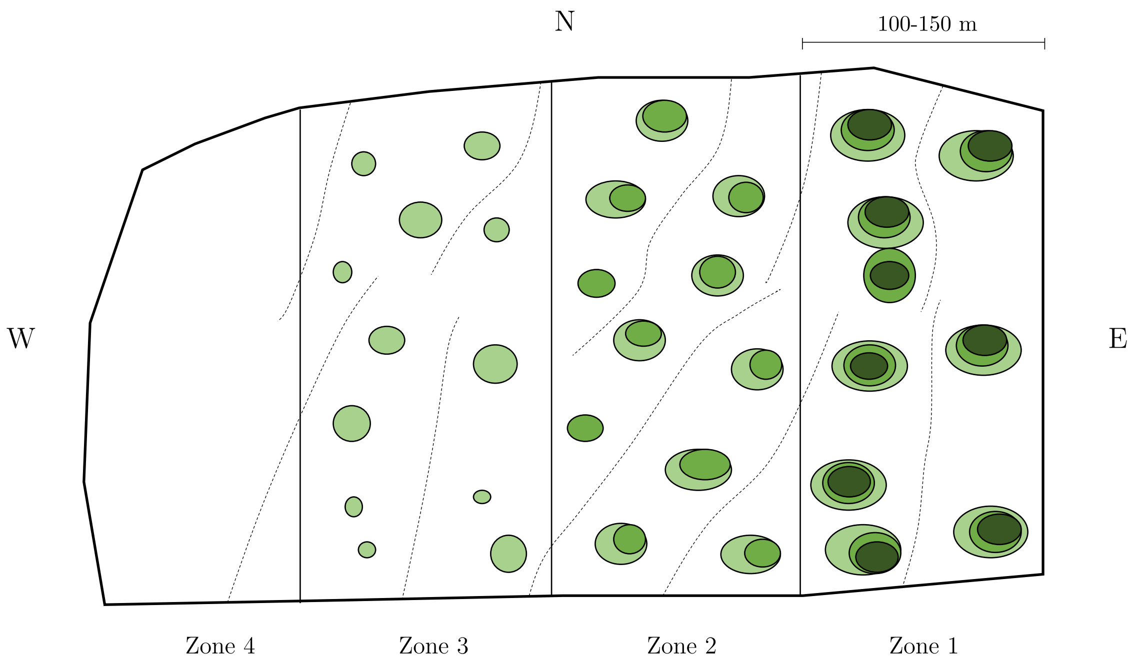

Fig. 5. Visual impression of a compartmentalised silvicultural system, i.e. a group system operating in progressive zones from east to west and using crescentic gaps. The darker the green of gaps or gap zones, the older the gap or gap zone and the corresponding regeneration. Thin continuous black lines are zone boundaries, dashed black lines are extraction racks. Modified from Drozdowski (2018).

new one in the same intervention. With the compartmentalised version of the strip system, for example, it is common to cut analogous strips simultaneously in all zones of a forest stand (Wagner, 1912; Smith et al., 1997).

4.2. Shelterwood inside and outside gaps

Group and strip system can be combined with the shelterwood system in two different ways (Table 2): (1) It is possible to (temporarily) retain residual mature trees in the gaps or strips so that they protect seedlings and cast partial shade (*shelterwood inside*). This could be useful for regenerating shade-tolerant and shade-intermediate species, particularly when the gaps are large. Such systems would be referred to as *group shelterwood* or *strip shelterwood system*. The shelterwood component is usually rather small and similar to that of the seed-tree/retention system, i.e. 5–10 mature trees per hectare. Another option (2) is to cut all mature trees in groups or strips, and to apply the uniform shelterwood system outside the gaps or strips (*shelterwood outside*). This strategy can be applied by starting with a uniform shelterwood system (akin to preparatory fellings, see Section 2.3) to encourage the regeneration of shade-tolerant and intermediate tree species. Once the first seedlings have appeared in sufficient densities more or less throughout the stand

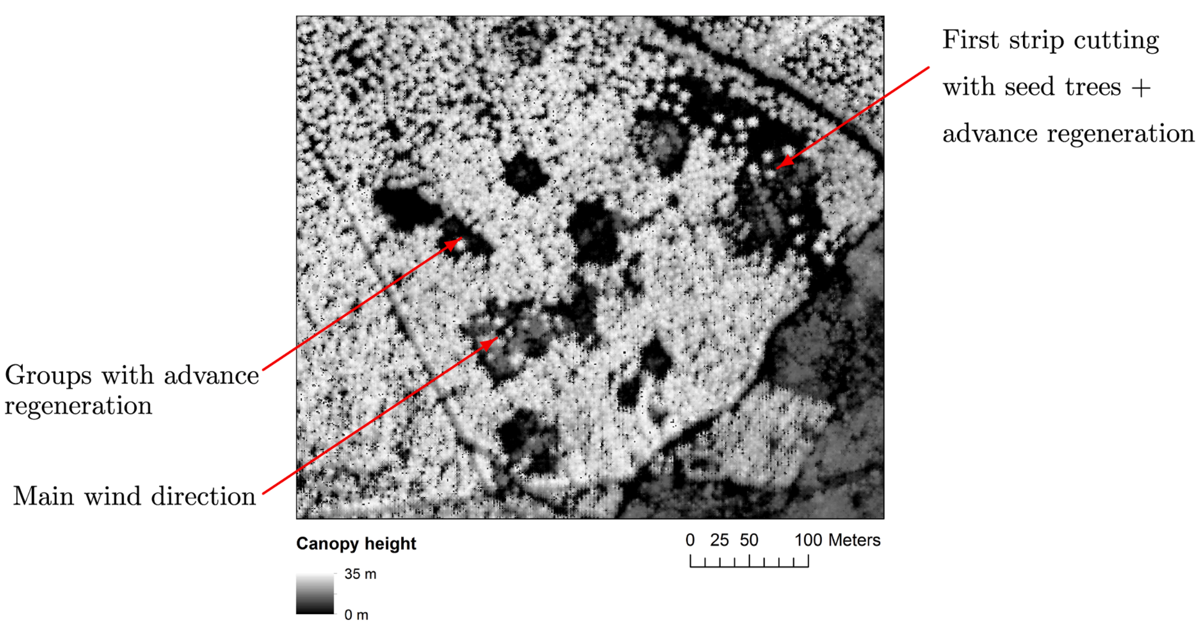

Fig. 6. Example of the early stages of a group-strip shelterwood system with Sitka spruce (*P. sitchensis* (Bong.) Carr.) in progress. LiDAR-derived canopy height model (1-m spatial resolution) for block 3, Cefn Du, Clocaenog Forest, North Wales, UK in 2006. Modified from Pommerening and Grabarnik (2019). Courtesy of Rachel Gaulton.

Table 3
Classification of frequently applied silvicultural systems inspired by the Polish classification system (Bernadzki, 2000; Puchalski, 2000) but modified for generic and international applications. The numbers are taken from Polish forest practice.

Lead system	Components	Name	Characteristics
Clearcut	Clearcut	Large-scale clearcut	Area: ≤ 6 ha, zone width: 60–80 m
Uniform shelterwood	Uniform shelterwood	Uniform shelterwood	Area: ≤ 6 ha, zone width 150 m
	Shelterwood outside + strip	Strip-uniform shelterwood	Not specified
Strip	Strip + clearcut	Large strip-clearcut	Area: ≤ 3–4 ha, strip width: 30–60 m
	Strip + clearcut	Small strip-clearcut	Area: ≤ 2 ha, strip width: ≤ 25–30 m
	Strip + shelterwood inside	Large strip shelterwood	Area: ≤ 4 ha, strip width: 30–60 m
	Strip + shelterwood inside	Small strip shelterwood	Area: ≤ 2 ha, strip width: up to 30 m
Group	Group (static) + clearcut	Group system	Area: ≤ 6 ha, zone width ≤ 80–100 m
	Group (dynamic) + shelterwood	Group shelterwood	Area: ≤ 6–9 ha, zone width 100–150 m
	Group (dynamic) + selection	Irregular shelterwood	Area: 5–30 ha, zone width 100–200 m
Selection (plenter)	-	Single tree selection	Area: 1–30 ha
	-	Group selection	Area: ≤ 40 ha

area and are secured, strips or gaps are cut progressively from the leeward end by removing the whole mature overstorey to create opportunities for light-demanding species. Alternatively uniform shelterwood cuttings can also be initiated several years after gap cuttings to grant the regeneration in gaps a growth head start over that in the surrounding matrix which is important for light-demanding species (Pommerening, 2023; Burschel and Huss, 1997; Bartsch et al., 2020). Combinations involving the uniform shelterwood system are often attractive, since this system can simply be the result of continued selective thinnings in the overstorey and is often used for preparatory cuttings (see Section 2.3) to encourage uniform seed production and dispersal when getting started. Combinations of silvicultural systems pursuing the second option would be referred to as *group-uniform shelterwood system* and *strip-uniform shelterwood system*.

4.3. Group-strip system

A combined silvicultural system that has been successful in a wide range of contexts is the group-strip system (Fig. 6). In this system, groups are opened up to 100–150 m well into the stand from the leeward edge. They can be cut at the same time or with a time difference of a few years. A strip is then initiated from the same sheltered edge approximately at the same time as the groups or a few years later. As the strips advance towards the windward edge of the stand, existing groups are expanded, and new groups are cut up to 100–150 m ahead of strips. Any advance regeneration in the groups is gradually absorbed by the progressing strips, thus introducing more diverse vertical and horizontal structure.

Although canopy gaps are opened and enlarged, potentially risking increased turbulence and wind damage, they advance from the relatively well-protected leeward side of the stand and are additionally strengthened by the system of progressing strips (Troup, 1928; Pommerening, 2023). Naturally it is also possible to cut static instead of dynamic gaps (both concentric and crescentic gaps are options, see Section 3). Rittershofer (1999) pointed out that the groups are usually given a higher priority than the strips and strip cutting commences after the first set of groups are in place and regeneration in groups is underway. Using a variant of the group system, it is possible that the initial groups were not cut but resulted from localised disturbances (see Table 1) so that strip cuttings could resume immediately. This combination of methods provides an enlarged regeneration frontier along with a wide range of growing conditions for tree species with differing demands and can give rise to heterogeneous stands. There is further combination potential, for example, by retaining shelterwood components in the groups and on the strips. This would already be a threefold combination of silvicultural systems, i.e. group + strip + shelterwood inside, and particularly this threefold combination has been quite successful across different species and environmental conditions (Burschel and Huss, 1997). The name *group-strip shelterwood system* (Fig. 6) is applied to this complex combination.

5. Classification example from Poland

Bernadzki (2000), Puchalski (2000) and Drozdowski (2018, 2022) proposed a classification of frequently applied silvicultural systems that has been successfully introduced into Polish forest practice. This classification is a good example of how to flexibly design silvicultural systems, including their variants and combinations, and how they can be made understandable to and operational for forest practice. To emphasise this point, we 'translated' the Polish classification into a more generic system for international use based on the terminology of Sections 2-4 of this paper (Table 3).

Most silvicultural systems of Table 3 are additive (spatial, see Section 2.5) combined systems, i.e. the components are implemented approximately at the same time or with a temporal difference of only a few years. For better clarity we have specified the *lead system* in the first column of Table 3. The lead system is expected to have the largest influence on the combined silvicultural system and on the resulting structure of the new forest generation after the silvicultural system has been completed. The lead system usually also comes first in the list of components and in the name of the system.

The characteristics given in Table 3 include the typical operational forest areas involved in the silvicultural systems in Poland and may need to be refined for use in other countries. In this column, the term *zone* again applies to temporal progression areas (with average turnovers of 10 years, see Section 4.1) whilst the term *strip* relates to systems that include the strip system.

Large-scale clearcut, the uniform shelterwood and the two variants of the selection system are the only basic silvicultural systems in the Polish classification. Variants of these systems are often applied but without combinations and it makes therefore sense that they are included in the classification. Combining the strip system with the clearcut system is a common way to break down large unsightly clearcut areas and to make this system more amenable allowing light-demanding (*Pinus* spp., *Betula* spp.) or intermediate (*Picea* spp.) tree species to regenerate naturally. A considerable step away from clearcutting is the strip shelterwood system where a sparse shelter of residual mature trees is sustained on the strips. The Polish system distinguishes between large (width of 30–60 m) and small (width ≤ 30 m) strip variants in these two systems.

The uniform shelterwood system is included in the Polish classification in its basic form and as strip-uniform shelterwood system. Here, the uniform shelterwood system is in principle the lead system, but for linguistic reasons the strip component comes first in the name. The strips are cut as small, localised clearcuts whilst the surrounding matrix is managed according to a uniform shelterwood system. Applications of strip-uniform shelterwood systems, i.e. a combination of large strips + shelterwood outside, can often be observed in mixed-species forests of *Fagus sylvatica*/*Quercus* spp. and *Pinus sylvestris*/*Picea abies* in Poland. In this country, *Picea abies* forests under optimal environmental conditions can be successfully regenerated naturally using strip-uniform shelterwood systems (Bernadzki, 2000).

The group system is part of the Polish classification as a basic system using the variant of static gaps that do not expand once they have been cut. In this variant, groups are essentially small clearcuts (0.05–0.5 ha) in the mature stand which are replanted by tree species not occurring in the stand (e.g. *Quercus* spp. or *Fagus sylvatica*). This variant is especially recommended for the conversion of monocultures to mixed-species stands with the majority of species being light-demanding. The remaining mature trees outside gaps are then usually rapidly removed. The second group system in the Polish classification is the group shelterwood system (group system + shelterwood inside), where a few mature trees are left inside the gaps providing shelter. In addition, mature trees outside gaps can be removed by shelterwood cuts, i.e. another combination level is added (group system + shelterwood inside + shelterwood outside).

Several versions of the irregular shelterwood system were included in the original Polish classification that mainly differed in size so that they can be applied to forests with complex forest structure and species compositions of diverse species proportions. Apart from a selection-system component they also include a more flexible way of gap and strip cuttings. The strip component is particularly suitable for *Picea abies* regeneration. We collapsed all these versions into one which can be applied freely as the manager sees fit.

Finally the two main variants of the selection (plenter) system are provided in the Polish classification. The single-tree selection system is recommended for *Abies alba* forest stands and the group-selection system is commonly used in situations where also light-demanding tree species are involved.

6. Discussion

As regeneration methods silvicultural systems still play an important role in silviculture and conservation where the active manipulation of forest structure through management is carried out to give rise to new tree cohorts (Troup, 1928). Many such methods have been developed throughout the world, usually as localised approaches on a trial and error basis (Puettmann et al., 2009). The uptake of regeneration methods has often been hindered by inappropriate descriptions of fixed “package deals” and the use of poorly defined and ambiguous terminology (Troup, 1928).

Our review revealed that it is possible to identify the basic building blocks and ingredients of silvicultural systems which facilitate their flexible assemblage based on a bottom-up approach and thus pave the way for new ones. The knowledge of basic components and their effects also enables the flexible active adaptation of existing silvicultural systems (variants) and the creation of combinations in direct response to local environmental conditions. Silviculturists and forest practitioners should be encouraged to experiment with silvicultural systems by freely assembling their basic components in any way that appears to be best to address specific environmental and other challenges.

The basic components of silvicultural systems can theoretically be considered treatment factors in statistical analyses, e.g. in the analysis of variance (ANOVA; Montgomery, 2013). This consideration could lead to interesting statistical experiments testing the appropriateness of various components of combined silvicultural systems in a given woodland community whilst deliberately moving away from the earlier trial and error approach. Although such an analysis is highly desirable, the practical implementation is not straightforward, since silvicultural systems require comparatively large areas (see Table 3) to operate. On average the minimum area required is 5 ha. In such comparatively large areas, mensuration would need to resort to remote sensing and or to sampling methods (transects) based on small plots which introduce a degree of uncertainty. In Poland, *control units* of one hectare size or less are placed in the centre of regeneration areas or forest stands for measuring the effects of silvicultural systems, i.e. a compact sub-area is used for that purpose.

Most modern combined silvicultural systems are additive (Rittershofer, 1999, p. 255), i.e. they are implemented at the same time but in different parts of the forest stand or zone. In some combinations of the uniform shelterwood system and the strip/wedge system (Wagner, 1912), substitutive approaches have been suggested in the sense that a uniform shelterwood system was established in the first instance which was then progressively replaced by the strip or wedge system (Rittershofer, 1999). However, the questions whether components of silvicultural systems should be implemented simultaneously or asynchronously or with a certain temporal overlap, much depends on local conditions and are clearly part of the local adaptation and design process.

Even more recent silvicultural and conservation methods such as variable density thinning (VDT; Palik et al., 2021; Willis et al., 2018) can be interpreted by means of the basic terms and ingredients of silvicultural systems presented in this paper. Variable density thinning, as it currently stands, is a combination of no thinnings (so-called skips), uniform shelterwood thinnings of different intensities and the group system using the variant of static canopy gaps that are not enlarged. Considering its main components one might be inclined to term VDT as a variant of the group-uniform shelterwood system. Based on the concepts reviewed in this paper, additions such as the use of dynamic canopy gaps or strips are possible to integrate in future VDT designs.

It is also interesting to note that most silvicultural systems that seemed to have originally been developed for high forests have a parallel in or can (with few modifications) also be applied to coppice or low forests (see Section 2.6). Historically it may often well have been the other way round, i.e. that silvicultural systems that we now know as high forest systems had their origin in coppice management and are therefore much older than we think (Mantel, 1990; Hasel and Schwartz, 2006; Bartsch et al., 2020). This is very likely to be the case for the selection forest system, as Schütz (2001) pointed out. As coppice management requires tree species that can regrow from roots or dormant buds, the species choice in low forests is somewhat but not excessively restricted. Particularly the application of combined high-forest silvicultural systems to coppice woodlands has the potential to increase biodiversity compared to traditional coppice management. In the context of conservation and CCF, there is currently renewed interest in low-forest management (Vanbeveren and Ceulemans, 2019; Vollmuth, 2022).

With time, variants and combined systems have also paved the way towards less formalised and more flexible ad-hoc methods of regeneration establishment where the manager responds more freely to arising needs without being required to stick to fixed, formal boundaries that were previously delineated (Bartsch, 2020, p. 545). In the past, attempts to rigidly formalise silvicultural systems and to dogmatically enforce their uptake (often out of self-assured hubris) have been largely unsuccessful, mostly due to their unsuitability when applied throughout larger regions without individual adaptation to local conditions and partly due to widespread professional resistance to dogmas in general (Puettmann et al., 2009). This development away from silvicultural formalism, particularly in countries with a long professional experience with regeneration processes and CCF, can, for example, be observed in Switzerland, where the Swiss irregular shelterwood system promoted by Engler and Leibundgut has largely become a code word or front for abandoning formalised silvicultural systems altogether. The Swiss irregular shelterwood system uses both individual-tree and group cuttings and is in principle a flexible and relaxed variant of the selection system, which – in its original form – is often inflexible when implemented in larger forest areas (Bauer, 1968). Like in selection systems, in the application of the Swiss irregular shelterwood system there is little spatial separation between working towards regeneration and other management objectives such as thinnings. An important element of such flexible, modern applications of silvicultural systems is to leave resilient mature overstorey trees behind for as long as possible. These trees provide a reliable framework ensuring the resilience of the whole regeneration process (Schütz, 2001). Strip cuttings are largely banned in Switzerland (Bauer, 1968).

Experience from countries, where close-to-nature or continuous cover forestry is new, shows that formalised silvicultural system play a much greater role (Kerr, 1999) here than in countries where CCF has been a standard for many decades such as in Central Europe (Bartsch, 2020). This is related to the well-known fact that formal recipes help reduce uncertainty and increase confidence in situations where the forestry profession lacks long-term experience with natural regeneration processes.

Formalised silvicultural systems are also increasingly abandoned in favour of new and specialised questions as the experience with regeneration processes grows. In the refined management of mixed-species forest stands, for example, it is not sufficient to obtain just any regeneration but to achieve appropriate seedling densities and the desired species composition. With ongoing climate change and the society's interest in conservation and recreation balancing tree species diversity is becoming more and more important. Achieving this objective requires a great deal of experience and silvicultural skill.

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CRediT authorship contribution statement

Arne Pommerening: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Janusz Szmyt:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Marie-Stella Duchiron:** Writing – review & editing, Writing – original draft, Investigation.

Declaration of competing interest

The authors declare that they have no known financial interests or personal relationships that could have influenced the work reported in this paper.

Data availability

No quantitative data were used for the research described in the article.

References

Andrzejczyk, T., 2006. Rębnia przerębowa w drzewostanach sosnowych. [Selection management in pine stands]. Sylwan 8, 52–60.
Ameray, A., Bergeron, Y., Valeria, O., Montoro Girona, M., Cavard, X., 2021. Forest carbon management: A review of silvicultural practices and management strategies across boreal, temperate and tropical forests. Curr. For. Rep. 7, 245–266.
Bartsch, N., Lüpke, v.B., Röhrig, E., 2020. Waldbau auf ökologischer Grundlage. [Silviculture on an ecological basis], 8th edition. Verlag Eugen Ulmer, Stuttgart.
Barzdajn, W., Drogoszewski, B., Zientarski, J., 1993. Struktura wielopokoleniowych drzewostanów sosnowych (*Pinus sylvestris* L.) w Nadleśnictwie Gubin. [Structure of the multi-generational pine stands (Pinus sylvestris L.) in the Gubin Forestry District] Prace Komisji Nauk Rolniczych i Komisji Nauk Leśnych, 76, 11–23.
Barzdajn, W., Zientarski, J., 2007. Wielogeneracyjne drzewostany sosnowe jako forma ochrony siedlisk leśnych. [Multiple-generation pine forests as a form of forest habitat conservation]. Studia i Materiały Centrum Edukacji Przyrodniczo-Leśnej 9, 325–335.
Bauer, F.W., 1968. Waldbau als Wissenschaft. [Scientific silviculture], 2. BLV Verlag, München.
Bernadzki, E., 2000. Ciecia odnowieniowe – poradnik leśniczego. [Regeneration cutting – a forester's guide], 2nd edition. Państwowe Wydawnictwo Rolnicze i Leśne, Warsaw.
Burschel, P., Huss, J., 1997. Grundriss des Waldbaus. [Outline of silviculture]. Parey Buchverlag, Berlin.
Ceitel, J., Perz, B., 2006. Sposób Mortzfeldta przebudowy składu gatunkowego drzewostanów. [Mortzfeldt's method for the conversion of species composition of stands]. Sylwan 7, 23–34.
Czachorowski, M., Drozdowski, S., 2021. Zagospodarowanie drzewostanów sosnowych (*Pinus sylvestris* L.) w zmieniających się uwarunkowaniach środowiskowych i społecznych. [Management of Scots pine (*Pinus sylvestris* L.) stands under changing environmental and social conditions]. Sylwan 165, 355–370.
Drozdowski, S., 2018. Rębnia stopniowa [Irregular shelterwood system]. Biblioteczka leśniczego, Wydawnictwo Świat Warszawa, 319.
Drozdowski, S., 2022. Rębnia ciągła w gospodarstwie leśnym [The selection system in forest management], 413. Biblioteczka leśniczego, Wydawnictwo Świat, Warszawa.
Ezquerro, M., Pardos, M., Diaz-Balteiro, L., 2019. Integrating variable retention systems into strategic forest management to deal with conservation biodiversity objectives. For. Ecol. Manage 433, 585–593.
Franklin, J.F., Forman, R.T.T., 1987. Creating landscape patterns by forest cutting: Ecological consequences and principles. Landsc. Ecol. 1, 5–18.
Gayer, K., 1886. Der gemischte Wald, seine Begründung und Pflege, insbesondere durch Horst- und Gruppenwirtschaft. [The mixed forest, its establishment and tending, particularly through group management]. Paul Parey, Berlin.
Hasel, K., Schwartz, E., 2006. Forstgeschichte. Ein Grundriss für Studium und Praxis. [Forest history: An outline for university students and practitioners], 3rd edition. Norbert Kessel, Remagen-Oberwinter.
Joyce, P.M., Huss, J., McCarthy, R., Pfeifer, A., 1998. Growing broadleaves. Silvicultural guidelines for ash, sycamore, wild cherry, beech and oak in Ireland. COFORD, Dublin.
Kautz, H., 1921. Die Verjüngung und Pflege der Buchen- und Fichtenhochwaldbestände im Schmalschlagbetriebe in der Oberförsterei Sieber (Harz). [Regeneration and tending of European beech and Norway spruce stands in the Sieber Forest District (Harz mountains) using the strip shelterwood system with narrow strips]. Zeitschrift für das Forst- und Jagdwesen 53, 348–406.
Kautz, H., 1922. Die Verjüngung der Buche und Fichte im Harz. [Regeneration of European beech and Norway spruce in the Harz mountains]. Zeitschrift für das Forst- und Jagdwesen 54, 93–106.
Kerr, G., 1999. The use of silvicultural systems to enhance the biological diversity of plantation forests in Britain. Forestry 72, 191–205.
Kerr, G., Morgan, G., Blyth, J., Stokes, V., 2010. Transformation from even-aged plantations to an irregular forest: the world's longest running trial area at Glentress, Scotland. Forestry 83, 329–344.
Köstler, J., 1956. Silviculture. Oliver and Boyd, Edinburgh.
Leibundgut, H., 1966. Die Waldpflege. [Forest Management]. Verlag Paul Haupt, Bern & Stuttgart.
Mantel, K., 1990. Wald und Forst in der Geschichte: Ein Lehr- und Handbuch. [Woodlands and forests in history: A textbook and guide]. Verlag M. & H. Schaper, Hanover, 1990.
Matthews, J.D., 1991. Silvicultural Systems. Oxford University Press, Oxford.
Mayer, H., 1984. Waldbau auf soziologisch-ökologischer Grundlage. [Silviculture on a sociological-ecological basis], 3rd edition. Gustav Fischer Verlag, Stuttgart.
Montogomery, D.C., 2013. Design and analysis of Eeperiments, 8th edition. John Wiley & Sons, New York.
Mortzfeldt, F., 1896. Über horstweisen Vorverjüngungsbetrieb. [Artificial regeneration in groups]. Zeitschrift für Forst- und Jagdwesen 28, 2–31.
Mosandl, R., 1984. Löcherhiebe im Bergmischwald. [Canopy-hole cuttings in mixed mountain forests]. Forstliche Forschungsberichte München, 61.
Newton, A.C., 2007. Forest ecology and conservation. A handbook of techniques. Oxford University Press, Oxford.
Nieuwenhuis, M., 2000. Terminology of forest management. IUFRO World Series Vol. 9-en. IUFRO Secretariat, Vienna, Sopron.
Nyland, R.D., 2002. Silviculture. Concepts and applications, 2nd edition. Waveland Press, Long Grove.
Olofsson, L., Langvall, O., Pommerening, A., 2023. Norway spruce (*Picea abies* (L.) H. Karst.) selection forests at Siljansfors in Central Sweden. Trees. For. People 12, 100392.
Palik, B.J., D'Amato, A.W., Franklin, J.F., Johnson, K.N., 2021. Ecological silviculture. Foundations and applications. Waveland Press Incorporation, Long Grove.
Petersen, R., Guericke, M., 2004. Untersuchungen zur Wuchsdynamik und Verjüngung der Fichte in Plenterstrukturen. [Influence of selection cutting on growth and regeneration in uneven-aged stands of Norway spruce]. Forst und Holz 59, 58–62.
Pommerening, A., Grabarnik, P., 2019. Individual-based methods in forest ecology and management. Springer Nature, Cham.
Pommerening, A., 2023. Continuous cover forestry: Theories, concepts and implementation. John Wiley & Sons, Chichester.
Puchalski, T., 2000. Rębnie w gospodarstwie leśnym. [Cutting systems in forest management]. Państwowe Wydawnictwo Rolnicze i Leśne, Warszawa.
Puettmann, K., Coates, K.D., Messier, C., 2009. A critique of silviculture. Island Press, Washington.
Reininger, H., 2001. Das Plenterprinzip. [The selection principle]. Leopold Stocker Verlag, Graz.

Rittershofer, F., 1999. Waldpflege und Waldbau für Studium und Praxis. [Forest management and silviculture for university students and practitioners], 2nd edition. Gisela Rittershofer Verlag, Freising.
Schütz, J.Ph., 2001. Der Plenterwald und weitere Formen strukturierter und gemischter Wälder. [The selection forest and other forms of structured and mixed forests]. Parey Buchverlag, Berlin.
Schütz, J.Ph., 2006. Modelling the demographic sustainability of pure beech plenter forests in Eastern Germany. Ann. For. Sci. 63, 93–100.
Schütz, J.Ph., Pommerening, A., 2013. Can Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) sustainably grow in complex forest structures? For. Ecol. Manage 303, 175–183.
Smith, D.M., Larson, B.C., Kelty, M.J., Ashton, P.M.S., 1997. The practice of silviculture: Applied forest ecology, 9th edition. John Wiley & Sons, New York.
Spiecker, H., Hansen, J., Klimo, E., Skovsgaard, J.P., Sterba, H., v Teuffel, K. (Eds.), 2004. Norway spruce conversion – Options and consequences. Koninklijke Brill NV, Leiden.
Sterba, H., Zingg, A., 2001. Target diameter harvesting – a strategy to convert even-aged forests. For. Ecol. Manage 151, 95–105.
Streit, K., Wunder, J., Brang, P., 2009. Slit-shaped gaps are a successful silvicultural technique to promote *Picea abies* regeneration in mountain forests of the Swiss Alps. For. Ecol. Manage 257, 1902–1909.
Szymański, S., 1992. Wyjaśnienia do rębni stopniowych wprowadzonych do Zasad Hodowli Lasu z 1988 r. [Explanations of the gradual forms of felling introduced in the principles of silviculture]. Sylwan 6, 59–62.
Troup, R.S., 1928. Silvicultural systems. Oxford University Press, Oxford.
Twaróg, J., 2003. Przesłanki optymalnego wyboru rębni w lasach polskich Karpat. [Preconditions for optimal choice of the cutting system in the Polish Carpathian forests]. Sylwan 2, 30–38.
Vanbeveren, S.P.P., Ceulemans, R., 2019. Biodiversity in short-rotation coppice. Renewable and Sustainable Energy Reviews 111, 34–43.
Vanselow, K., 1949. Theorie und Praxis der natürlichen Verjüngung im Wirtschaftswald. [Theory and practice of natural regeneration in managed forests]. Neumann Verlag, Berlin.
Vítková, L., Ní Dhubháin, Á., 2013. Transformation to continuous cover forestry: A review. Irish Forestry 70, 119–140.
Vollmuth, D., 2022. The changing perception of coppice with standards in German forestry literature up to the present day – from a universal solution to a defamed and overcome evil – and back? Trees. For. People 10, 100338.
Wagner, C., 1912. Der Blendersaumschlag und sein System. [The strip shelterwood system]. Verlag der H. Laupp'schen Buchhandlungen, Tübingen.
Willis, J.L., Roberts, S.D., Harrington, C.A., 2018. Variable density thinning promotes variable structural responses 14 years after treatment in the Pacific Northwest. For. Ecol. Manage 410, 114–125.
Wilson, E.R., McIver, H.W., Malcolm, D.C., 1999. Transformation to irregular structure of an upland conifer forest. The Forestry Chronicle 75, 407–412.