may be bottlenecks of labor or machinery. Even if there were no such restrictions, it makes sense to sell wood when the price is high and to minimize harvesting when the price is low. In other words, some stands may be felled long before their optimum rotation and others may be felled a lot later. A specialist branch of forestry is concerned with estate modeling, which varies the rotation length of individual stands to ensure both continuity of supply for the whole forest and responsiveness to market signals.

Consider a processing plant that handles large, old logs (perhaps it requires clearwood with a high proportion of heart). It pays a very high price for the wood, and is a dominant customer of the forest. It requires a regular, predictable supply of this type of wood.

The resource forester examines the inventory records of the whole forest and observes that there is an impending gap in the supply of this log grade, followed soon after by a glut. This is because no real forest exists where there is a perfectly balanced mixture of age classes. Disruptions such as planting booms, wars, depressions, storms, or fires always mean that there is a higher proportion of certain age classes, and gaps where there are no trees of optimum age. What to do? The answer may be to overcut the oldest age classes, followed by undercutting the next oldest. In other words, in order to satisfy the major customer and fill the gap in supply, some age classes will cut well before their optimum rotation age and others many years afterwards.

The forester's decision has long-lasting consequences. Not only does it greatly influence the asset value, the cash flow, and the profitability of the existing resource, but it also has a major bearing on the next generation of trees. This is because a planting boom immediately follows a harvesting boom, because land cannot be left idle for long without weed encroachment. The existing age class structure of the forest is creating headaches for planners, but it behoves them also to consider the effect of their actions on their successors.

Summary

The issue of rotation age is a good example of the complexity of forest science. To the uninitiated, forestry may seem like a simple business ('you plant a tree and you cut it down') but a deeper examination reveals the difficulties of determining and imposing rational solutions on long-lived biological systems. The measurements, calculations, and models in forestry can be highly complex but can never reach the degree of precision that could be attained in purely physical systems. Also, the payback periods envisaged by the forester are significantly longer than almost any other human endeavor. What factory, what engineering structure, what work of art, would take three decades or more to commission?

See also: **Afforestation**: Stand Establishment, Treatment and Promotion - European Experience. **Ecology**: Reproductive Ecology of Forest Trees. **Plantation Silviculture**: Short Rotation Forestry for Biomass Production; Sustainability of Forest Plantations. **Silviculture**: Unevenaged Silviculture.

Further Reading

Evans J and Turnbull JW (2004) *Plantation Forestry in the Tropics*. Oxford (3rd edition) [Chapter 18].
Matthews JD (1989) *Silviculture Systems*, Oxford.
Savill PS, Evans J, Auclair P, and Falck J (1997) *Plantation Silviculture in Europe*. Oxford. [Chapter 10]
Smith DM (1986) The Practice of Silviculture. Wiley (8th edition).

Multiple-use Silviculture in Temperate Plantation Forestry

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Introduction

Silviculture can be defined as the growing and tending of forest stands to meet management objectives. One of the characteristics of forests is that they can be managed to meet a wide range of objectives, from timber production to provision of recreation opportunities, from conservation of rare species to sheltering farm animals during harsh weather. In recent decades, a common tendency has been to try and zone forests into areas of 'dominant use' where a particular objective would take precedence over all the others. Thus recreation might be the most important objective close to a forest visitor center whereas the emphasis would be on timber production in areas with little public access and low visibility. Management for these contrasting objectives might foster stands that would vary appreciably between zones. Thus stands in the first zone might be very variable over a short distance with a range of tree species of different sizes, whereas the second would have much less spatial variation with more regular stand structures composed of one to two species. This approach may be termed 'single' or 'dominant use' silviculture where the aim is to maximize the yield of a particular output (visitor days or volumes of timber) subject to providing minimum levels of any other outputs. However, it is often possible and desirable to manage stands for several objectives at the same time, for instance by providing a habitat with an attractive landscape that accommodates game shooting and where regular harvests of timber provide income for the owners. This alternative strategy is called 'multiple-use' silviculture because managers explicitly seek to develop stands that will provide for a range of uses at the one time. The purpose of this short review is to explain some of the increasing interest in 'multiple-use' silviculture and outline some of the challenges to its wider adoption. The emphasis is upon experience in the British Isles, but the principles should be applicable in other countries and forest types.

Plantation Forests: An Example of Dominant Use Silviculture

A frequent legacy of national forestry policies during the nineteenth and twentieth centuries is extensive areas of conifer plantations that were established in many parts of the north temperate zone to provide a wood supply for local industries. Examples of such plantations can be found in Britain, Ireland, The Netherlands, Belgium, Germany, New Zealand, Chile, South Africa, and many other countries (**Figures 1** and **2**). The plantations created during this era of forest expansion have often developed into homogeneous stands of trees of similar ages ('even-aged') of one or two species. The main silvicultural system used in their management has been clear-felling. Under this system all the trees on a given area (coupe) are felled and removed from site when they have reached the desired size for processing. The average coupe size can vary from less than 1 ha to up to 50 ha or more, depending upon location and visibility. The felled area is generally reforested by planting young seedlings that have been raised elsewhere in a forest nursery. However, if the chosen tree species produces regular supplies of seed, and if the site is of low fertility so that weed competition is not serious, then reforestation may be achieved through natural regeneration. In either case, the aim is to ensure rapid growth of the young trees so that a full canopy cover is restored. Any competing vegetation or unwanted tree species are normally removed during the establishment phase. In a similar way, any trees of poorer quality of lesser vigor are gradually thinned out after canopy closure so that by the time of clear-felling, the stand is composed only of the better-quality stems. The age at which clear-felling occurs (rotation age) varies with species and site but in the north temperate zone is generally between 40 and 120 years.

Figure 1 Cawdor. An internal view of a 100-year-old Scots pine plantation in north-east Scotland managed under a group shelterwood system. The mixture of mature trees and clumps of regeneration of pine and other species provides a varied woodland which is both attractive to the local community for recreation and a source of valuable timber for the landowner. Courtesy of the Forestry Commission.

Recent changes in forest policy in many countries have given much greater emphasis to the sustainable management of existing forests for multiple benefits, including maintenance and enhancement of biodiversity, provision of recreational opportunities, and increased visual diversity, as well as timber production. There has been ongoing criticism that the limited number of tree species and the lack of structural diversity within the stands of plantation forests is not compatible with management for multiple objectives. A particular concern has been that the relatively short rotations employed have resulted in a lack of older stands and the rich habitats

Figure 2 Glenbranter. An 80-year-old Sitka spruce stand in western Scotland which is starting to develop some of the features of the later phases of stand development. Note the large trees, the regeneration in the background, the fallen deadwood, and the developing ground flora which all combine to provide some of the features aspired to in multiple use silviculture. Courtesy of the Forestry Commission.

associated with features such as large trees, abundant deadwood, and an open stand structure. Such criticisms have been particularly strong in countries where plantation forests are a major part of the forest area as in Great Britain and Ireland, or where the natural forest stands have been gradually simplified towards a structure similar to a planted forest (e.g., Scandinavia, parts of Central Europe). As a result, there has been a growing perception that conventional plantation silviculture based upon clear-felling may not be the most effective way of delivering multiple benefits, particularly in forests with high landscape, recreation, or conservation values. This has led to increasing interest in the use of a range of alternative silvicultural systems to clear-felling such as shelterwood and selection systems, all of which involve retaining some mature trees on the site during the regeneration phase. This approach has been given a variety of names such as 'continuous cover forestry,' 'close-to-nature forestry.' and 'ecological silviculture,' to name but a few.

Stand Dynamics and Multiple-Use Silviculture

A better understanding of these issues is gained by considering the development of a forest stand over time, otherwise termed stand dynamics. While this is a complex process with appreciable variation between both forest types and regions of the world, a comparatively simple conceptual model in widespread use separates the development into four distinct phases. These are generally known as stand initiation, stem exclusion, understory reinitiation, and old-growth with the first being the youngest and the last the oldest stage in the process. It is not inevitable that a stand has to develop through all four phases since damage caused by a major disturbance (e.g., the wind storms of 1987 in southern England and of 1999 in France and Germany) will destroy so much of the overstory that a stand reverts back to the initiation phase.

Table 1 gives more details of these phases using a Scottish Scots pine (*Pinus sylvestris*) stand as an example. A point to notice is that a forest will generally contain stands at different stages of this development process, depending upon the history of harvesting or natural disturbance due to fire, wind, snow, or disease. The frequency of such disturbances can affect the relative area of stands in the different phases. Thus an area with frequent severe disturbances from wind or fire will have comparatively few stands in the old-growth phase and more in the younger phases than would be the case where such events are less frequent.

The traditional practice in timber management of harvesting a stand at or close to the age of maximum mean annual volume increment tends to occur towards the end of the stem exclusion phase. Management would also seek to maximize the return on investment by reducing the length of the stand initiation phase. The impact of this silvicultural approach can be examined by looking at the way a range of timber and other benefits change with different stand development phases (**Figure 3**).

In this figure, the variation of an illustrative range of market and nonmarket benefits is presented in relation to these four phases for Sitka spruce (*Picea sitchensis*) plantation forests in northern Britain. The benefits are not quantified, but the relative values are supported by findings from studies on public preference and biodiversity carried out in Great Britain and elsewhere in the last decade. For example, timber value peaks in the stem exclusion and early understory reinitiation phases but declines towards old-growth. By contrast public preference is lowest in the

Table 1 An outline of the four phases of stand development using a Scots pine (*Pinus sylvestris*) stand in northern Scotland as an example. Reproduced with permission from Mason WL (2002) Silviculture and stand dynamics in scots pine forests in Great Britain: Implications for biodiversity. *Investigacíon Agroria; Sistemas y Recursos Forestales* Fuera de serie no. pp 175–198

Phase	*Approximate tree age (years)*	*Approximate height of dominant trees (m)*	*Comments*
Stand initiation	0–20 (40)	0–5	The period during which the trees are becoming established on the site, but a closed canopy has not yet been formed. The longer period refers to what happens when natural regeneration is being used and/or the trees are being affected by browsing.
Stem exclusion	20–80	5–20	The trees form a closed canopy over the site. No shrub or tree understory is present. Tree death will occur as a result of competition unless this is reduced by thinning.
Understory reinitiation	80–150	20–25	Gaps start to occur in the canopy as a result of disease or disturbance. Regeneration of pine and other tree species can occur. Height growth has slowed down but diameter growth continues.
Old growth	150–350 (or more)	25 or more	The survivors of the original trees begin to die out. The stand becomes a mosaic of groups of trees each of different ages. Comparatively low stocking compared to the previous two phases. Increasing abundance of standing and fallen deadwood.

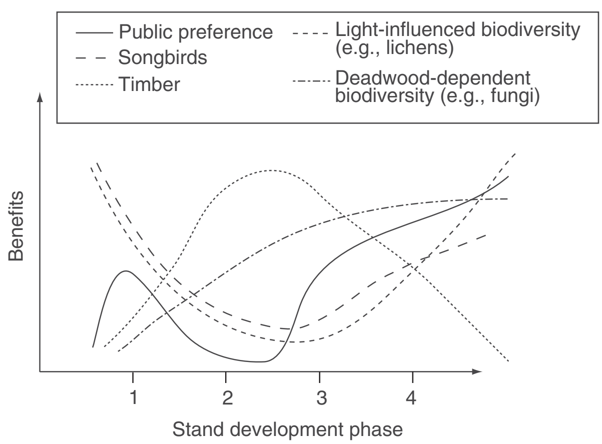

Figure 3 The changes in relative magnitude of selected benefits with different stand development phases in Sitka spruce (Picea sitchensis) plantations in Scotland. Phase 1, stand initiation; 2, stem exclusion; 3, understory reinitiation; 4, old growth. See text for further details.

stem exclusion phase and highest in the stand initiation and old-growth phases. Deadwood-dependent biodiversity is highest in the old-growth phase.

These relationships also suggest that management regimes that produce forests dominated by stands of a particular phase will not produce as wide a range of benefits as could be achieved if all the development phases were represented. This has particular implications when alternative silvicultural systems to clear-felling are being evaluated for possible use in forest management.

Silvicultural Systems and Multiple-Use Silviculture

As noted earlier, there is a range of silvicultural systems that can be used to manipulate stand structure to meet objectives. For the purpose of this discussion, three main systems can be distinguished although there are many local and regional variants, and one type can often intergrade into another. These are:

1. The clear-felling system where a particular area of a forest is cleared in a single operation and is generally followed by replanting.
2. The shelterwood systems where again a particular area of forest is cleared, but in this case the process involves a number of regeneration fellings designed to promote natural regeneration.
3. The selection systems where selective felling of trees is being carried out and natural regeneration is being fostered over the whole forest area.

In general terms, these systems provide different proportions of the various stand phases and therefore different flows of benefits. Thus, a clear-felling system provides a forest with stands that are predominantly moving from the stand initiation to the stem exclusion phase and back again. Stands in the later phases can be provided if stands are retained beyond normal rotation age, but once they are felled they return to the stand initiation phase. By contrast, a shelterwood system, with regeneration occurring either under the canopy of the mature trees or in gaps adjacent to these trees, provides some characteristics of the understory reinitiation phase. Once the regeneration is established, the overstory trees are generally removed so that the stand reverts to a stem exclusion phase. Depending upon the extent of the regeneration fellings and the amount of the overstory that is retained, the area in the stand initiation phase can be appreciably reduced compared to that found under a clear-felling regime. A selection system differs again since one essential aim is to foster and develop regeneration in small gaps so that the whole stand is predominantly in the understory reinitiation phase. Finally, in a broadleaved plantation, one also has the option of introducing a coppice system where the combination of mature trees and different sizes of underwood can provide features of all stand development phases except old growth.

Therefore, if one is seeking to introduce multiple-use silviculture to a forest previously managed for timber production using a clear-felling system, introduction of one of the alternative systems on a percentage of the area will change the proportion of the various stand phases in that forest. This is generally likely to increase the range and spread of benefits being obtained. For example, the recent colonization of many plantation forests in upland Britain by the goshawk (*Accipter gentilis*) is associated with the retention of more stands into the early understory reinitiation phase. By contrast, uncritical adoption of an alternative system can imperil species dependent upon particular habitats. In pine forests in lowland Britain, populations of the rare wood lark (*Lullula arborea*) require the bare ground conditions associated with stand initiation following clear-felling. Greater use of shelterwood or selection systems would limit the amount of such open habitat and could reduce the population.

The various silvicultural systems produce stand structures which show different horizontal and vertical distributions of features such as foliage, branches, open space, and stand microclimate. All of these can influence factors like the growth of a tree, the habitat available for a given organism, or the spiritual enjoyment of the forest. The clear-felling system will produce stands that are more homogeneous than those produced by the other main systems. Thus, in a 50-year-old Sitka spruce plantation nearing felling age which has been managed for timber production with regular thinning, the spacing between trees will be uniform, and there will be relatively little variation in tree height or diameter. The tree crowns will intercept about 90% of incident light so that there is little vegetation growth on the forest floor and there will be no other tree species present in the canopy. By contrast, in a stand of the same species being managed on a selection system to produce large dimension timber (i.e., 60 cm diameter at breast height), there will be a wider range of diameters and heights associated with trees of different ages, and the light climate may vary considerably where overstory trees have been harvested and regeneration is developing.

A point that emerges from this discussion is that none of the systems as traditionally formulated is designed to provide the old-growth phase and associated deadwood habitat which is increasingly recognized as lacking in many forests that have been intensively managed for timber production. This is not to say that the systems cannot be adapted for this purpose, but rather that one needs to understand the range of stand structures that can be produced by each system and that mix of structures which is appropriate to provide a sustained flow of market and nonmarket benefits.

Site Classification, Mixtures, Native Species, and Multiple-Use Silviculture

Since the interest in adopting multiple-use silviculture often occurs in response to reactions against plantation forest management for timber production, this is often accompanied by attempts to increase the species diversity of such forests. A common aspiration is to convert single-species stands into mixtures and to increase the percentage of native species in such forests.

However, the success of such aspirations is critically influenced by the availability of a site classification methodology that adequately reflects the ecological factors affecting tree growth in different regions and on varying soils. Without such knowledge, it is difficult to decide which species can be appropriate for use in mixture and at which stage in a stand development life cycle it is most effective to introduce them. For example, in northern Britain there has been increasing interest in the potential of introducing birches (both *Betula pendula* and *B. pubescens*) into Sitka spruce plantations to increase visual amenity and species diversity. These species are broadly compatible with Sitka spruce in terms of site fertility but are less tolerant of wind exposure. Both birches can be found colonizing clear-felled sites in the stand reinitiation phase and can persist into the early stem exclusion phase in areas that have been replanted with Sitka spruce. However, examination of height growth curves for these species shows that they are unlikely to compete with Sitka spruce in the long term and that intimately mixed species stands of birch and spruce are unsustainable in the stem exclusion phase. Therefore, it appears that a strategy for increasing the percentage of birch in spruce forests would need to be based around the creation of pure stands of birch within a spruce matrix. Such stands would need to be large enough to provide for the development of mature trees to ensure a seed source whenever nearby harvesting or wind disturbance created an area for potential regeneration.

An understanding of the limiting factors on a site is essential if species diversification is to be successful as part of multiple-use silviculture. An example can again be drawn from the birch–Sitka spruce case in northern Britain. There have been a number of instances where spruce plantations were established on exposed sites with difficult access and the prospects for commercial timber production have proved limited. In such circumstances, conversion of the spruce plantation to a native birch forest should provide a better flow of benefits over time. However, clear-felling of the spruce and replanting with birch has been problematic, largely because the removal of the spruce has resulted in a loss of stand microclimate and the birches have suffered from the wind exposure. Site assessments indicate that a more certain, if longer-term approach would be to establish birch within gaps developed within the spruce plantation and progressively remove the conifer matrix, possibly over 10–20 years.

A further point that is raised by these examples is that the introduction of multiple-use silviculture into plantation forests requires an ability to consider what the 'future-natural' state of the stands is likely to be, particularly if it is anticipated that such forests will continue to be managed with timber production as one of the objectives. In countries where the plantations are dominated by nonnative species and/or little natural forest remains, then it may not be obvious what are the appropriate species to introduce into the plantations, let alone what pattern of mixture or silvicultural system should be employed. In such situations, a site classification which can provide objective guidance on species suitability will prove an invaluable aid.

Challenges to Greater Use of Multiple-Use Silviculture

As outlined in the previous sections, successful adoption of multiple-use silviculture requires a grasp of the stand dynamics of the particular forest type(s), an appreciation of how different benefits are affected by silvicultural system and stand development phase, and an understanding of how silvicultural options are limited by site conditions. However, even where these prerequisites have been achieved, there are still a number of serious challenges to be considered. These are:

1. The need to relate the desired structures at a stand level to the wider pattern that is appropriate for a whole forest or catchment. As shown in **Figure 1**, the various phases of stand development each provide a different mix of benefits and it is generally unrealistic to expect a single stand or small forest area to provide the whole range of potential benefits. Therefore, some thought has to be given to the various benefits that are to be provided at a whole landscape level and how the flow of benefits is to be sustained over time. Such an approach can be difficult enough when the landscape unit is managed by a single landowner, but it becomes very complex when there are a number of owners with contrasting objectives.
2. An assumption underpinning the link between the landscape and stand levels is that it is possible to agree what should be an acceptable mix of stands in the different phases and how these might be distributed over a forested landscape. Reference is often made to using natural disturbance regimes for a given region (e.g., the return periods for damaging winds) as a means of calculating the proportion of stands in different phases. Unfortunately, this approach requires good knowledge on disturbance history which is often lacking or can be an artifact of past forest management. Examples of the latter include a reduction in fire frequency because of fire suppression policies or an increase in wind damage because of delayed thinning.
3. Forest management in the last century tended to simplify stand structures in many forest types in the interests of increased timber production as has been shown by numerous studies in Scandinavia and North America. Therefore a major silvicultural challenge is to identify and foster stands that can eventually provide the structures characteristic of the understory reinitiation and old-growth phases. In particular, there is a lack of guidance on the potential structural and spatial features of old-growth stands in areas where plantation forests have been created. It is unclear whether the development of such features can be accelerated through stand manipulation practices such as thinning to produce a variable spatial distribution of trees (variable density thinning). The best location for and the appropriate size of such stands in a forested area also requires to be considered.
4. Successful application of multiple-use silviculture will require better understanding of the way key outputs from the forest are influenced by silvicultural practices. For example, adoption of continuous cover forestry systems may seem desirable to avoid the visual impacts associated with clear-felling, but dense natural regeneration within such stands might produce a closed and less attractive internal forestscape for walkers. The complex

interactions between stand structures and desired outputs mean that managers will need to be certain which are the key species, values, and products which their forests are to provide. They can then propose how such outputs will be affected by changes in stand structure achieved through silviculture, decide which mix of interventions is most appropriate, carry these out, and monitor the results after a suitable time interval. The silvicultural prescriptions may then be changed as a result of the information provided by the monitoring.

5. This highlights the need for decision support tools that are capable of simulating the development of stands under contrasting management regimes and that can be linked via a geographic information system (GIS) to show the flow of benefits over space and time from particular strategies. For instance, widespread adoption of a selection system might produce stands that were very heterogeneous at a small scale, but a landscape that was monotonous and where species dependent upon the stand initiation phase were underrepresented. Better understanding of how different benefits are influenced by stand structure is important here since silvicultural interventions seek to provide those structures that are thought to fulfill management objectives. Criteria for success in even-aged plantation management are well researched and described for many forest types in the world, but equivalent aids for multiple-use silviculture are rare.

In the last analysis, successful implementation of multiple-use silviculture requires the development of a shared future vision for a forest that can be used to inspire the public, employees, and various stakeholders. In areas such as the British Isles where the area of native woodland is small and fragmented, it is unrealistic to expect the native woods to provide the social and environmental benefits while the considerably more extensive area of plantation forests is managed largely as a wood factory. Instead, the plantation forests have to be diversified through multiple-use silviculture to provide the mix of benefits required by commitments to sustainable forest management. The challenge for foresters in such situations is not whether to adopt multiple-use silviculture, but rather how to do it and where best to begin the process.

See also: **Biodiversity**: Plant Diversity in Forests. **Ecology**: Natural Disturbance in Forest Environments; Plant-Animal Interactions in Forest Ecosystems; Reproductive Ecology of Forest Trees. **Genetics and Genetic Resources**: Forest Management for Conservation. **Landscape and Planning**: Forest Amenity Planning Approaches; Landscape Ecology, Use and Application in Forestry. **Recreation**: User Needs and Preferences. **Silviculture**: Natural Stand Regeneration. **Social and Collaborative Forestry**: Social Values of Forests.

Further Reading

Bell S (2003) *The Potential of Applied Landscape Ecology to Forest Design Planning*. Edinburgh, UK: Forestry Commission.

Humphrey JW, Holl K, and Broome A (1998) *Birch in Spruce Plantations: Management for Biodiversity*. Forestry Commission Technical Paper no. 26. Edinburgh, UK: Forestry Commission.

Hunter ML (1999) *Maintaining Biodiversity in Forest Ecosystems*. Cambridge, UK: Cambridge University Press.

Kelty MJ, Larson BC, and Oliver CD (1992) *The Ecology and Silviculture of Mixed Species Forests*. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Kimmins H (1992) *Balancing Act: Environmental Issues in Forestry*. Vancouver, Canada: University of British Columbia Press.

Kohm KA and Franklin JF (1997) *Creating a Forestry for the Twenty-First Century*. Washington, DC: Island Press.

Matthews JD (1989) *Silvicultural Systems*. Oxford, UK: Oxford University Press.

Nyland RD (1996) *Silviculture: Concepts and Applications*. New York: McGraw-Hill.

Oliver CD and Larson BC (1996) *Forest Stand Dynamics*. New York: John Wiley.

Peterken GF (1996) *Natural Woodland: Ecology and Conservation in Northern Temperate Regions*. Cambridge, UK: Cambridge University Press.

Schütz J-P (1997) *Sylviculture 2: La Gestion des Forêts Irrégulières et Mélangées*. Lausanne, Switzerland: Presses Polytechniques et Universitaires Romandes.

Sustainability of Forest Plantations

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Introduction

Plantation Forests

The present extent of planted forests worldwide probably exceeds 180 million ha. New planting in both tropical and temperate regions is leading to a significant net increase of forest plantation each year. It is predicted that in time a greater proportion of industrial wood will be sourced from plantations than from exploiting natural forests, and that this trend towards increasing reliance on planted forest for wood production will continue. Thus forest