logs where growth since pruning has eliminated all appearance of nodal swelling, such logs being regarded as having increased their diameter sufficiently for knot-free timber to be recoverable. An example of detailed assessment is the Pruned Log Index used in New Zealand. This is derived from measurements of log size, log shape, and defect core size and relates directly to, but remains independent of, grade and value recovery by any sawmill. Application of this measure of pruned log quality resulted in mill door prices for pruned logs which ranged from $NZ140–215 m^{-3} (approx. $US75–115) during 2002.

See also: **Harvesting**: Harvesting of Thinnings. **Operations**: Ergonomics. **Plantation Silviculture**: Forest Plantations. **Plantation Silviculture**: Rotations; Stand Density and Stocking in Plantations; Tending. **Tree Physiology**: Physiology and Silviculture.

Further Reading

Evans J and Turnbull JW (2004) *Plantation Forestry in the Tropics*, 3rd edn. Oxford, UK: Oxford University Press.
Florence RG (1996) *Ecology and Silviculture of Eucalypt Forests*. Melbourne, Australia: CSIRO Publishing.
Helms JAI (1998) *The Dictionary of Forestry*. Bethesda, MD: Society of American Foresters.
James RN and Tarlton GL (eds) (1990) *New Approaches in Spacing and Thinning in Plantation Forestry*, Proceedings of an IUFRO Symposium. Rotorua, New Zealand: New Zealand Forest Research Institute.
Lewis NB and Ferguson IS (1993) *Management of Radiata Pine*. Melbourne, Australia: Inkata Press.
Montagu KD, Kearney DE, and Smith RGB (2002) The biology and silviculture of pruning planted eucalypts for clear wood production: a review. *Forest Ecology and Management* 6174: 1–13.
Savill PS and Evans J (1986) *Plantation Silviculture in Temperate Regions*. Oxford, UK: Clarendon Press.
Shepherd KR (1986) *Plantation Silviculture*. Dordrecht, The Netherlands: Martinus Nijhoff.
Smith DM (1962) *The Practice of Silviculture*. New York: John Wiley.

Rotations

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Introduction

When should a tree be harvested? At 'maturity'? Unlike animals, trees do not reach a maximum size and then stop growing, so the definition of 'maturity' is not clear. A tree can be harvested at any age that the owners consider desirable. The question of rotation age (also called rotation length) is very relevant for foresters and indeed has long been one of the main decisions that foresters are trained to make.

Because forests usually contain a mixture of species and age classes, they are more complicated than stands which can consist of even-aged trees growing from bare ground – like a crop of wheat. Starting with the simplest situation, a planted or naturally regenerated tree in an even-aged stand, there are several phases in the growth cycle.

Stages of Tree Growth

The first phase is site capture. Of the thousands, or tens of thousands, of seedlings per hectare, few trees can survive the initial years. The tree uses energy to put down roots, build up a green crown, and outcompete weeds. Access to water and nutrients is vital, but light is often not so limiting. Wood production is not of major survival benefit, and in any case the plant does not yet have the resources to generate high amounts of photosynthate. The tree expands until it encounters the influence of neighboring trees, at which point the rate of growth slows, for both the roots and crown. Weeds become suppressed and cease to be a major problem.

In phase 2, the tree can progress in only two ways: by competing with, and taking over the space of the neighbors, or by extending upwards. The tree's survival is guaranteed only if it can maintain access to light, water, nutrients, carbon dioxide, and space. For most species, light becomes critical, because a well-lit tree can acquire the energy to obtain the other resources. On the other hand, overtopping by neighbors will suppress and kill a tree. That is the main reason trees produce wood – survival advantage is ensured by gaining height and securing the light.

As the tree's height increases, the lower branches become shaded and die. A steady state is reached where growth at the top of the tree is matched by death at the bottom of the green crown. Nutrients are translocated upwards from branches as they become moribund. The important point for foresters is that trees in phase 2 require low inputs of minerals – most nutrients are used in the formation of the green crown, and little extra is required for either the maintenance of the crown, or for the production of wood. Wood is a carbohydrate, comprising overwhelmingly carbon, hydrogen, and oxygen and little else. Once the 'factory' has been constructed, good growth can be expected wherever there is adequate temperature, water, and sunlight.

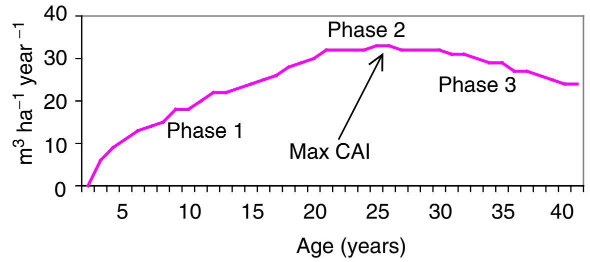

Figure 1 Annual stemwood growth (net current annual increment (CAI) and volume). Adapted from the New Zealand National Exotic Forest Description 1995. Although indicative of the weighted-average growth for radiata pine in New Zealand, the line has been smoothed for the sake of clarity.

But eventually the tree's increasing size and age come at an energy cost: water must be pumped from the root tips to the topmost foliage, and starch must be translocated the same distance in reverse. The tree's size makes it vulnerable to the effects of wind, and the wounds it has developed over its long life make it susceptible to attack by insects and disease. Its productivity drops off and it becomes senescent (phase 3). Thus there is a point in the life of an individual tree or stand where it is the most productive at growing stemwood (**Figure 1**).

Gross and Net Increment

The volume increment of the stand is measured per unit area (i.e., per hectare or per acre). Gross increment is the wood produced each year, and net increment is the same, less the quantity lost through death and decay. While individual trees may still be actively growing, other trees are dying, and the forester must consider the stand as a whole. The current annual increment (CAI) is the wood produced in the most recent year. The mean annual increment (MAI) at a given age is the CAI averaged up to that age. It is usually expressed in net terms, but can include the wood harvested from extraction thinnings. Such thinnings are a way of using, and preventing, loss from natural mortality.

Rotation Age for Maximum Volume

As the stand progresses from phase 1 to phase 2, and more resources are channeled into wood production, the CAI increases. As long as this is greater than the MAI, the MAI will continue to improve. At the point where the CAI has declined to equal the MAI, the MAI will have attained its maximum level (**Figure 2**). The point of maximum MAI is of great significance to foresters, because if all stands were harvested at this age then the forest would be producing the maximum sustainable volume.

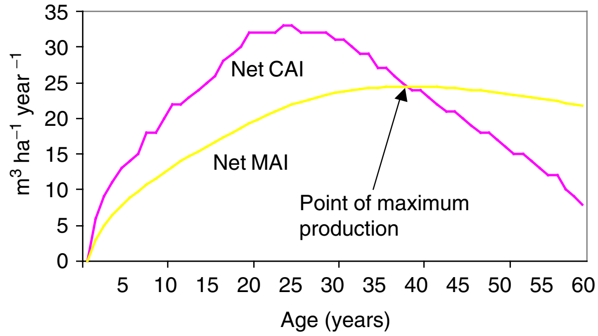

Figure 2 Rotation age to maximize production. CAI, current annual increment; MAI, mean annual increment. Adapted from New Zealand National Exotic Forest Description (1995). For the sake of clarity, the data have been smoothed and extrapolated past age 40.

For hundreds of years the main job of foresters in both Europe and China was to 'conserve the maturity' of the forest resource – to prevent trees being felled before they had reached their maximum potential. It is always tempting to overcut, i.e., cut more wood than the allowable volume that has been calculated by estimating the yield of a theoretical forest where the stands were harvested at their maximum MAI.

A healthy mixed-aged forest can sustain a certain level of production indefinitely, but assume that a greedy government or population cuts more wood than this figure. What effect does this have? The average harvest age is reduced, the productivity of the forest is diminished, and it will require greater and greater numbers of younger and younger trees to meet the same demand. If overcutting is allowed to continue, eventually trees only a few years old will be harvested. These will not provide nearly the same quality or quantity of wood as the original 'mature' forest.

At the other end of the spectrum, an overmature forest is also not productive. This means that it contains a high proportion of trees that are senescent or at risk from storm or insect damage. Overcutting this forest will, if done carefully, restore the forest's vigor, by returning the average rotation age to its peak value of MAI.

In practice it is difficult to calculate the age and amount of maximum MAI for any tree species. A huge database is needed, as growth rates vary with species, soils, climate, management regime, and genotype. Some of these are constantly changing. It is also difficult to quantify mortality. Some death and decay are inevitable, as a result of trees becoming more crowded. Trees naturally thin themselves out as they take up more space, and this can be predicted with a reasonable degree of accuracy. Such tree loss is called attritional mortality. Tree death also commonly occurs from storm events, from fire, drought, frost, and epidemics of disease and pests. If large numbers of trees die, this is called catastrophic mortality. The distinction between the two types is vague, and in any case the two types influence each other. The significance of the latter is that it is inherently unpredictable and cannot easily be built into models.

Even if the forester overcomes these difficulties, the job is not complete. It is not sufficient to determine the rotation age that will provide the greatest quantity of wood from a given area of forest in perpetuity. Wood quality must also be considered. Revenue at harvest is a combination of both quantity and quality.

Rotation Age for Maximum Harvest Revenue

Generally speaking, the older the tree, the better the quality of wood, unless the tree has started decaying. Wood density is an important attribute, being a determinant of strength, stiffness, and hardness. It increases with tree age: the outer growth rings are denser than the inner rings. The proportion of heartwood also increases with tree age. Heartwood is noteworthy because it imparts durability and color, depending on species. Heartwood can be yellow, brown, black, red, or combinations of these. This contrasts with sapwood, which is generally a bland white and is nondurable. In addition to these well-known qualities, a number of other characteristics, such as moisture content, spiral grain, and distortion in processing, become less problematic with maturity. Most importantly, the lower branches of very old trees die and fall off, with subsequent wood being knot-free ('clearwood').

Wood is sold in distinct grades, with log specifications that relate to straightness, number of growth rings, heartwood content, branch presence and size, and small-end diameter, among other considerations. Often there are substantial price differences between successive log grades, which may correspond to different end-uses. The stumpage revenue at clear-felling therefore does not increase smoothly with age: it may remain fairly flat over several years and then rise sharply when a critical threshold of wood quality is attained.

Near the time of harvest, the value and value increment of a stand need not be predicted from generalized silvicultural models – it can be obtained more directly from inventory models. Individual trees often display features that are inherently unpredictable, so generalized models have limited utility. For example, a tree may have a predictable height and diameter at breast height, with an excellent butt-log up to a certain height, but upper logs are downgraded by lack of straightness, woodpecker holes, or other stem damage. Average branch size may be predictable, but individual large branches or forking (possibly induced by a storm event affecting most trees in the stand at a certain height) are not so amenable to mathematical modeling. Good inventory models will optimize the value of individual trees when cut into logs. Although these models may amalgamate data to describe the whole stand, they will simulate future growth without losing the detail obtained from an inventory of individual, idiosyncratic trees.

The output of intensive measurement and modeling for mature stands is an accurate assessment of standing value, currently and for a decade into the future. While the volumes by log grade are predictable by this process, any projection of prices is fraught with difficulty. One can use current prices, or prices averaged over the last (say) 12 quarters, or prices obtained from a trendline, or prices estimated from anticipated market conditions.

Rotation Age for Maximum Profitability

An astute forester will take all these things into consideration when determining rotation age, but the task is still not complete. The combination of quantity and quality of wood provides the revenue at harvest for a range of ages, but it is necessary also to consider cost, risk, and the time interval between costs and returns.

Maintaining a forest is not usually free of costs. Imagine a forest where stands are harvested at 60 years of age. The forester calculates that the revenue will improve if stands are harvested at age 80. But to do this each stand has to undergo 20 years of extra fire protection, land taxes, and supervision. The investment carries an extra 20 years of risk: the older stands could be susceptible to disease or storm damage. Most critically of all, the revenue will need to be deferred for 20 years, and time is money. This difficult concept needs some explanation.

Faced with an offer of $1000 today or a promise of $1000 in 1 year's time, most people would take the former. The money can be used right now for paying off debt, for investing in another project, or obtaining interest via somebody else's investment. In the jargon, people have a time preference for early returns. A rational time preference can be calculated by examining the compound interest on alternative investments. This is called the cost of capital. In addition to the cost of capital, risk is sometimes included in the figure. For example, the $1000 today is certain, whereas the $1000 next year is only a promise. For all these reasons, future returns are heavily discounted, and the greater the investment interval, the higher the discount factor. It is important to understand that this is the major reason why rotation lengths in commercial forests are less than the point where revenue is maximized. The optimum rotation age financially is less than the optimum rotation age physically.

The Opportunity Cost of Capital

To illustrate this concept, let's consider the financial growth of a tree crop grown as an even-aged stand. As the crop grows, it becomes more valuable. The return on capital is the current value increment of the crop divided by its standing value. The current value increment increases, but eventually cannot keep pace with the gain in value of the stand. The ratio of increment to standing value increases to a maximum and then declines. The possibility of selling the asset and investing the money elsewhere becomes ever more tempting. This occurs well before the stand has reached its maximum MAI for value or even for volume. The complaint is often heard that a stand is being felled 'just when it is starting to show substantial annual gains in value,' and long before it has achieved its maximum average volume production. True, but is it gaining in value relative to the considerable – and increasing – value of the asset?

To reinforce this point, let's consider two mixed-age forests of the same species and growth potential. Forest A is grown on a rotation of 80 years, whereas forest B has a 40-year rotation. They are both managed sustainably, with a constant proportion harvested and replanted every year. Forest A has a greater proportion of older trees and has a standing value twice as high as forest B.

An accountant standing at the gates of the forests observes that daily inputs (i.e., costs) to each forest are the same, but the daily outputs are substantially different. The older forest is producing more wood every day, because the rotation age is closer to the peak of MAI.

Simple accounting would suggest that forest A is more profitable (revenue minus costs), but this is not necessarily the case. More capital is tied up in forest A. If this forest were liquidated (i.e., cut down and sold) it would sell at twice the price of forest B. It would be possible to use the money to buy two forests exactly like forest B. Thus it is not only important to maximize the output of the forest relative to daily costs, it is also important to minimize the capital tied up in the forest. The easiest way to do this is by maintaining a relatively low rotation age.

Foresters who calculate the internal rate of return (IRR) for a crop of trees at every rotation age often experience a sense of shock: the maximum IRR is found at very young ages – far lower than conventional wisdom would suggest. Rapid turnover of capital is of crucial importance in any calculation involving IRR: it is important to keep costs down, to delay costs, and to obtain revenue at the earliest opportunity.

An alternative approach is to use net present value (NPV), where the discount rate is specified. Discount rates used in forestry are commonly 6%, but can be 10% or more. The discount rate represents the real (i.e., inflation-adjusted) rate of return that foresters expect to get from alternative investments, plus a factor for risk. Rates of this magnitude may be reasonable for short-term investments, but the awesome exponential power of compound interest over the time spans implicated in forestry suggest that such rates are unreasonable for forestry and unsustainable for the general global economy. Be that as it may, the effect of using high discount rates is exactly the same as that of using IRR. It emphasizes the value of money upfront, and downplays the benefits of distant rewards.

Because many foresters throughout the world have used IRR or NPV at a high discount rate to determine their regimes, trees harvested from plantation forests are usually very young. This means they have a small diameter and are inferior for either structural or appearance uses. They are inferior in terms of strength, stiffness, and hardness because of their low wood density, among other characteristics. They are inferior for appearance purposes because they contain very little heartwood and very little knot-free wood (unless pruned). Short-rotation regimes can be justified as long as there is a good market for pulpwood and chip-and-saw grades, or as long as reconstituted wood can satisfactorily and cost-effectively substitute for the natural product, but it is conceivable that the predominance of short-rotation regimes could lower the price of this material and result in a premium for older and larger trees. It is also possible that there could be a swing away from the use of high discount rates in forestry.

Forests Versus Stands

One final point must be made regarding rotation age. A forest is more complicated than a stand, and the optimum solution for a forest may not coincide with the optimum solution for the stands within it. This is because there may be supply commitments, or there 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