other conditions in a country and region, and often according to the particular circumstances of individual owners.

See also: **Afforestation**: Stand Establishment, Treatment and Promotion - European Experience. **Harvesting**: Harvesting of Thinnings. **Mensuration**: Growth and Yield. **Plantation Silviculture**: Forest Plantations; Stand Density and Stocking in Plantations; Tending. **Wood Formation and Properties**: Wood Quality.

Further Reading

Assmann E (1970) *The Principles of Forest Yield Study*. Oxford, UK: Pergamon Press.

Evans J and Turnbull JW (2004) *Plantation Forestry in the Tropics*, 3rd edn. Oxford, UK: Clarendon Press.

Hamilton GJ (1976) The Bowmont Norway spruce thinning experiment 1930–1974. *Forestry* 49: 109–119.

Hamilton GJ (ed.) (1976) Effects of line thinning on increment. In *Aspects of Thinning*, Forestry Commission Bulletin no. 55, pp. 37–45. London: HMSO.

Kilpatrick DJ, Sanderson JM, and Savill PS (1981) The influence of five early respacing treatments on the growth of Sitka spruce. *Forestry* 54: 17–29.

Leban JM, Houllier F, Goy B, and Colin F (1991) La qualité du bois d'Épicéa commun en liason avec les conditions de croissance. *Forêt Entreprise* 80: 11–27.

Savill P, Evans J, Auclair D, and Falck J (1997) *Plantation Silviculture in Europe*. Oxford, UK: Clarendon Press.

Slodicak M and Novak J (2003) Thinning experiments in Norway spruce stands after 40 years of investigation: 1st series. *Journal of Forest Science* 49: 45–73.

Yoda K, Kira T, Ogawa H, and Hozumi J (1963) Self-thinning in overcrowded pure stands under cultivated and natural conditions. *Journal of Biology Osaka City University* 14: 107–129.

High Pruning

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Introduction

Pruning is a technique usually employed with the aim of enhancing the quality of solidwood products derived from the butt log of trees in forest plantations. The aim of the technique is to remove knots from the outer wood of such logs but it may also result in loss of growth when living foliage is removed or may introduce rot into the wood, especially in hardwood species. While pruning has been known for many years it is not commonly applied except where trees grow fast enough to provide returns that satisfy economic criteria. It is most common in New Zealand where most stands of radiata pine (*Pinus radiata*) are pruned and where a price premium for pruned logs has been established.

Pruning Defined

Pruning can be defined in straightforward terms as the removal, close to the stem, of living or dead branches from standing trees. The process of pruning is closely allied to that of 'brashing' which refers to the removal, by beating, of branches on a tree stem from ground level to a height of about 2 m. In some countries (e.g., the UK) the term 'high pruning' may be used to refer to pruning above the height where branches have been removed by brashing.

The definition clearly refers to the deliberate action of removing branches using tools designed for the purpose. Sometimes this is called 'artificial pruning' to distinguish it from the practice of natural branch shed which occurs in many species, particularly within natural stands over an extended period of time. Pruning has been known to and used by foresters for some time. It was mentioned by John Evelyn in 1664, in his book *Sylva*, in which he referred to pruning as having been practiced by the 'ancients.' It has been applied as a scientifically based technique for many decades and examples appear in modern literature from at least 1935. Despite its history, pruning is not a general practice in all parts of the world and although statistics are poorly recorded it seems to be mainly carried out in plantations of countries in the southern hemisphere such as Argentina, Australia, Chile, the Republic of South Africa, New Zealand, and Uruguay. These countries can obtain the fast individual tree growth necessary to provide a yield of improved timber within an economic time frame. In New Zealand, where pruning has been a prominent feature of plantation silviculture since the 1970s, over 1 million ha or two-thirds of the area of radiata pine plantation forest has received pruning treatment. As a consequence, the technology associated with pruning pine has been well developed in that country and much of the information presented here has come from New Zealand sources, including recent research papers.

Rationale for Pruning

Doubts about the economics of pruning usually preclude its use in natural forests although it is a frequent practice in urban forests where the main objective is improved access, increased visibility, and enhanced appearance. In plantations, branches are usually removed to a height of about 6 m and pruning may be carried out in a number of stages or 'lifts' to a specified height or diameter up the stem. Except for brashing where a club may be used, branches are usually severed by shears or saws. Even in plantations pruning may not be regarded as an essential operation. Where it is applied as part of stand silviculture it may be carried out for a number of objectives such as: a precaution against the spread of fire into the upper crown, to provide stand access, to reduce timber degrade, and finally as a planned series of operations aimed at eliminating or reducing the effect of knots as a source of degrade in sawn and sliced or peeled wood. (Additional, minor, but locally important objectives may include the use of the branches themselves as stock food, fuelwood or to obtain essential oils. Other special products can include cricket bats made from pruned willow and matchsticks from veneer peeled from pruned poplar.) Eliminating degrade and provision of high-quality wood are similar but the impetus to carry out pruning to reduce degrade implies that some features of the stand or its silviculture will cause the wood to be degraded by exceptionally large knots should pruning not be applied. An example is the pruning of 'stand edge' trees in South Australian plantations of radiata pine where the extra growing space resulting from roads, fire-breaks or other clear space adjacent to the stand may result in branch sizes much larger than those within the stand which are controlled by normal silviculture.

Application of Pruning Techniques

Pruning as a method of preventing the spread of fires, to provide access within the stand or obtain fodder or fuel does not require strict timing. However when the provision of clear, knot-free timber is the aim, then the pruning should be carefully programmed and carried out at times in the life of the stand which will result in the maximum size of a clearwood zone outside the 'defect core' of knotty wood.

The process by which clear, knot-free timber is produced by pruning is illustrated in **Figure 1**. When trees are young and stem diameter is small, branches are removed and, after a process of occlusion (or covering of the branch stub by continuing growth), normal stem growth continues with the new wood being free of knot defect. Since trees taper, pruning is usually carried out in lifts (generally two to four) to avoid enlarged cores at the base of the tree. Pruning should be scheduled to minimize the size of the defect core within the pruned zone yet retain sufficient foliage to permit the tree to continue with adequate

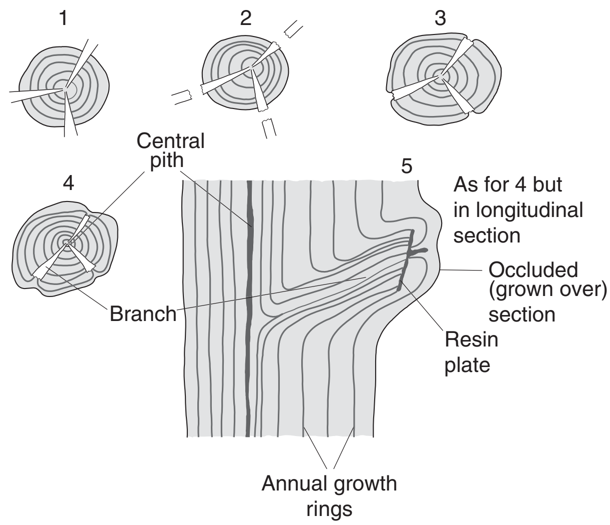

Figure 1 Production of knot-free 'clearwood' using pruning.

growth. Sawn timber or veneer recovery will also be enhanced if the maximum diameter of the defect core is the same for each lift. Since sawing and peeling are carried out effectively in straight lines, boards cut from the outside of the log will be knot-free until the saw encounters the limits of the defect core. Because sawn pieces are usually graded on the basis of the worst defect, the value of some boards would be reduced if they contained isolated defects caused by a diameter over pruned stubs which was larger than the others in the same pruning series. Thus an important component of efficient pruning technique is to time operations so that the maximum DOS is the same for all lifts. Models to predict maximum DOS have been developed and these are used for scheduling operations in plantations of radiata pine in New Zealand and Australia. These models are driven by the expected diameter of the tree at the base of each pruning lift or stage. This can be related to the tree or stand mean diameter at breast height, a parameter which is commonly measured or predicted during the course of forest management.

A pruning schedule which could be used for stands of radiata pine grown in eastern Australia is given in **Table 1**. The schedule is designed to result in a maximum diameter over pruned stubs of 18 cm for all three lifts. The stand is assumed to have been planted at 1000 stems ha^{-1} for a final crop of 200 stems ha^{-1}. Three thinnings are scheduled, two without yield and one, to 200 stems ha^{-1}, with yield in year 20.

The efficient production of knot-free wood can be achieved only if pruning is accompanied by rapid individual tree growth. This is achieved by thinning (or removing) all unpruned stems. As pruning is usually carried out when the trees are young and

Table 1 Schedule of silvicultural operations for radiata pine (*Pinus radiata*) in eastern Australia, featuring pruning to improve wood quality in the butt log

Age (years)	Silvicultural operation
0	Plant 1000 stems ha^{-1}
5.8	Prune 350 stems ha^{-1} to 2.2 m
5.8	Thin to 500 stems ha^{-1} residual stocking, without yield
6.7	Prune 275 stems ha^{-1} to 4.0 m
7.6	Prune 200 stems ha^{-1} to 5.8 m
7.6	Thin to 350 stems ha^{-1} residual stocking, without yield
20	Thin to 200 stems ha^{-1} residual stocking, with yield
30–35	Clearfell

DOS is small, the thinned trees may also be too small in diameter to provide a useful product and the thinning will be without yield (or 'to waste'). The example of a pruning regime given in **Table 1** has two such thinnings scheduled to occur at the same time as the first and third pruning lifts with the objective of reallocating stand growth to the pruned crop trees.

The total diameter of the defect core is however larger than just the DOS. It will be enlarged by any inclusion of resin or bark which is incorporated at time of occlusion and any exaggeration from stem crookedness. In the case of peeled veneer logs the defect core will also be exaggerated by noncentral pith. In conifers the presence of resin pockets within the clearwood zone may eliminate any improvement arising from pruning. Resin pockets (or streaks) are often typical of a particular location and may occur locally in excess; an effect seen in plantations of radiata pine and slash pine (*P. elliotii*). Pruning should not be applied on such sites.

The correct selection of crop trees, particularly of the straightness and most vigorous, and the combination of pruning with other silvicultural operations such as thinning so that growth is enhanced, is necessary to ensure that the benefits of pruning are maximized. When pruning is applied to improve wood quality, it should be applied over a complete commercial log length (with appropriate allowance for stump height and any applicable cutting allowance) to obtain full financial benefit. Pruning above the first or butt log is rare but has been carried out in countries where labor costs are low.

Effect of Pruning on Tree Health

In conifers the severed stub usually becomes coated with a layer of exuded resin which is generally sufficient to prevent fungal infection. This protective mechanism is not present in hardwoods and for some (e.g., the eucalypts, *Eucalyptus* spp.) the chance of rot occurring as a result of the pruning operation is quite high.

To avoid the formation of internal rot, it is necessary to adopt a quite different method of scheduling pruning of eucalypts. Eucalypts shed their branches under natural conditions and during the long rotations applied in extensively managed natural forests this is sufficient to provide defect-free timber. The process of natural branch shedding is well known. The branch dies and an abscission zone develops close to the trunk in which the xylem of the branch becomes blocked and subsequently brittle. With the growth of the stem, the branch becomes more horizontal in orientation and pressure from the continued growth of the trunk together with the weight of the dead branch eventually results in its ejection from the growing stem with a part of the branch occlusion zone remaining within the trunk. When pruning removes a dead branch there is no residual weight to ensure ejection and the short stub remaining outside the abscission point may be 'caught' by the enlarging stem wood and dragged outwards with continuing growth, leaving a kino-filled trace behind. This effect has been observed in both *Eucalyptus nitens*, a temperate eucalypt, and the tropical eucalypt *E. grandis*, although the rate of occurrence has not been established. While this effect negates the objective of pruning it can be counteracted by pruning only green (living) branches. When this is done the occlusion process is similar to that of conifers (**Figure 2**). The scheduling of pruning in eucalypts therefore involves 'chasing the green crown' or pruning before the natural death of branches occurs in the lower crown. Models of the change in height of the base of the green crown can be used to schedule pruning so that branches are pruned while they are alive.

However green pruning disrupts the natural protection from rot formation which, is afforded by the abscission zone in the natural branch shedding process. Research in both New Zealand and Australia has found decay associated with pruning especially the pruning of large (>2 cm) branches; although rot is mainly restricted to the defect core. Results from one study (in *E. nitens*) found that about half of the pruned trees will contain stem rot associated with at least one pruned branch. For some species pruning in the correct season may confer some protection from infection, e.g., *Prunus avium* is reported to suffer bacterial canker when pruned in winter or spring and should be pruned at other times. However results from surveys of eucalypts are conflicting on this aspect and a seasonal effect is yet to be established.

The effect of pruning on stability during windstorms is not clear. If there is an effect, it is probably

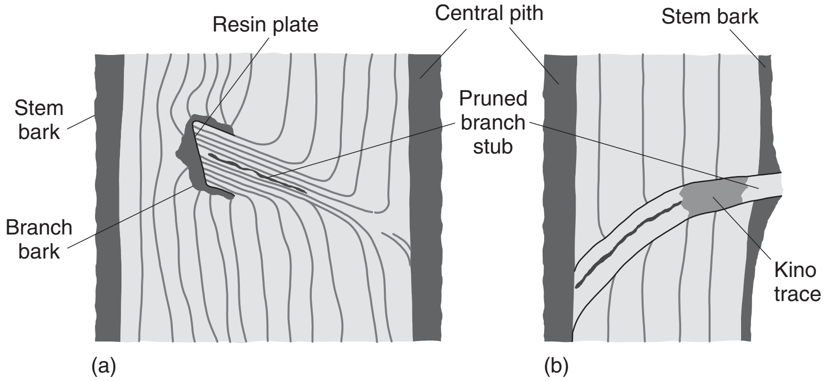

Figure 2 Detail of occlusion over pruned branch stubs in (a) *Pinus radiata*, (b) *Eucalyptus nitens*. (a) Shows normal conifer occlusion over a dead branch, (b) illustrates a frequent result when dead branches of a eucalypt are pruned. Redrawn with permission from Gerrand AW, Neilsen WA, and Medhurst JL (1997) Thinning and pruning eucalypt plantations for sawlog production in Tasmania. *Tasforests* 9: 15–34.

only found in young stands where the length of pruned stems represents at least one-quarter of total tree height. For older trees, especially where the lower branches of unpruned trees would be dead and leafless, there is probably no difference in susceptibility to storm damage between pruned and unpruned trees. In young trees pruning could:

- reduce the crown surface area and hence the area on which the wind could exert pressure
- allow greater air movement through the lower stand in the pruned zone
- lessen the energy-absorbing effect of tree to tree canopy contact
- elevate the center of gravity and center of bending moment and thus alter the natural sway of the tree.

The net effect of these theoretical possibilities is unclear as observers have found both greater and lesser damage amongst pruned trees within stands that have suffered damage from windstorms.

Pruning Tools and Methods

The tools used for pruning are mostly simple hand-operated tools such as shears or saws. The shears may be of the double-fulcrum type and either one or two cutting blades may be used. If saws are used they may be self-supporting blades with a short or long handle and commonly with back-raked teeth (which cut on the pull stroke). Alternatively they may be of the frame and tensioned blade type. Ladders are used to support the operator when branches are pruned above 2 m. This is more efficient than using saws mounted on poles (*see* **Operations**: Ergonomics). In the past a number of striking tools such as axes or modified slashers have been used. The use of these has largely been discontinued because of the damage caused to the stem, the irregular surface of the cut branch, and the danger to the operator.

There have been a number of attempts to mechanize the operation of pruning, but with little success. The necessity for repeat visits to carry out each lift, lack of easy access to trees under forest conditions, and the difficulty of building a power unit without the disadvantages of weight, noise, vibration, air pollution, and the danger inherent in motorized cutting tools have precluded mechanization on an operational scale. Although lightweight chainsaws are sometimes used for the first, ground-based, lift, especially where branches are large, the inherent danger of this operation and the restrictions imposed by safety regulations mean that it is not a widely applied method. Recent developments in electronics have led to one method of power-assisted pruning that is currently used in Argentina and Chile. Power is supplied by a set of lightweight (about 3 kg) rechargeable batteries which is carried on a waist-band and shoulder harness and which powers shears similar to those used by some types of hand shear. Studies carried out in Argentina have shown that while productivity increases are marginal, the workers are less fatigued and achieve target rates more easily, and the workforce need not be restricted to the 'fit young male' category. The forestry version of this tool is a modification of equipment developed in France for vineyard pruning and used for that purpose in many other countries.

Effect of Pruning on Tree Growth

When living branches are severed in pruning there will inevitably be a reduction in tree foliage. Although this lower foliage may be less photosynthetically active than that of the upper crown, there may be some loss of increment as a result. This effect has been well established for many species (both hardwoods and softwoods) throughout the world. Some experimental results suggest that almost any level of foliage removal will result in at least some reduction in tree growth. However other results suggest that removal of inefficient lower foliage may result in some increase in tree growth. The necessity of obtaining a small defect core will usually require that some of the 'green crown' (or living foliage) be removed even if this results in some growth loss. For pines, regimes are often designed to ensure that a 4-m length of green crown is left after pruning. For eucalypts, where the mechanism for scheduling is focused more on the height of the base of the living crown than diameter over pruned stubs, removal of 40–50% of the length of the green crown has been identified as an acceptable compromise. Physiological changes within the remaining foliage have been noted probably leading to increased photosynthetic efficiency in the residual crown. In any case, where reduction of growth has been observed, the effect has been temporary. Of more concern than this temporary reduction in growth is the permanent loss of tree stem dominance status. That is, when trees that were selected for pruning because of their dominance are left to compete with unpruned trees, they are liable to lose dominance because the loss of foliage has slowed their growth and reduced their ability to compete with the unpruned stand component.

Removal of living foliage may stimulate the growth of epicormic branches within the pruned zone. In pines these arise from stem-borne needle fascicles and in hardwoods from dormant buds beneath the bark. It is common practice to use a knife to remove needle fascicles from pine stems when pruning branches and for both pines and hardwoods to remove epicormic branches that have formed since the last pruning lift.

Growth is derived from the foliage of the crown, and crown length per hectare has been found to be correlated, on a stand basis, with growth for young stands of New Zealand grown radiata pine. Although the relationship is not a simple one it has been used as the basis for models which can be used to predict the early growth of stands and particularly the effect of early pruning and thinning on subsequent growth.

The Economics of Pruning

The decision whether or not to incorporate pruning into a silvicultural regime will depend on an assessment of the financial benefits, including the improvement in returns from pruned compared to unpruned logs. A study which investigated the effects of various parameters on estimates of pruning profitability (plantation grown radiata pine in New Zealand) using a silvicultural modeling system found that profitability was not particularly sensitive to total pruned height or diameter over pruned stubs but in both cases the volume yield of clear grades was sensitive to these effects. The lesser effect on financial estimates was probably a result of trade-offs between costs and production effects. Price assumptions and interest rate markedly affected estimated profitability.

As there are few firmly established premiums for pruned logs estimates of future prices are usually regarded as a matter of informed conjecture. Since pruning involves considerable investment and results will not be obtained for some years, the decision to prune involves some risk. One source of price information is the New Zealand Ministry of Agriculture and Forestry which publishes averaged prices received for New Zealand grown radiata pine, on a quarterly basis. Based on data as at June 2002, there was a premium of about $US50 m^{-3} (Japanese Agricultural Scale, free on board) for pruned export logs and $US36 tonne^{-1} (mill door) for pruned domestic logs.

While premiums have been established for some markets, it is a matter of judgment whether they will be available more generally or whether they will be sufficient to compensate for the cost of the investment in pruning. Some utilization companies are using technology instead of pruning to improve the appearance of sawn wood. This can include cutting out knots and finger-jointing the shortened lengths into boards, covering boards with a plastic sheet on which has been printed a photographic image of knot-free wood and extruding defect-free components from wood pulp. Some would regard such solutions as less aesthetically pleasing than wood from pruned trees.

Even when margins for pruned logs have been established, pruned log quality must be determined before the margin is realized. This may be achieved from presentation of silvicultural records. The Pruned Log Certification Scheme which has been established in New Zealand is a record system that allows evaluation at time of sale. For the certification scheme, parameters that would indicate the quality of pruning (such as the average diameter over pruned branch stubs) are assessed immediately after pruning has taken place and records are held by authorities independent from the forest owner. Prospective purchasers can use these records and the size of the trees at time of felling to estimate the yields of high-quality timber. Assessment at time of sale varies from simple pragmatic rules-of-thumb, to sawing of samples, to detailed measurement of the internal and external properties of sample logs. An example of pragmatic assessment is the acceptance of pruned 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.