Stand Density and Stocking in Plantations

K Theron and B V Bredenkamp, Department of Forest Science, University of Stellenbosch, South Africa

Introduction

In the third volume of the classical work *Schlich's Manual of Forestry* (1925), it is stated:

> To every method of treatment, as determined by the objects of management, corresponds a normal density of the growing stock. The degree of density may be defined as overcrowded, crowded, open, very open, interrupted, irregular, etc. Such terms are indefinite and subject to different interpretations.

Over 75 years later the terms describing the degree of site occupancy by trees are still being misinterpreted, essentially because many foresters use 'stocking' when referring to 'stand density.' These terms are not synonymous and are well defined. Stand density is an absolute measure that quantitatively expresses the number or count of trees on a unit of land, for example x stems per acre (spa) or y stems per hectare ($\mathrm{s\,ha^{-1}}$). If trees are well spaced so that death from competition mortality is precluded, then stand density will remain constant over fairly long periods of time.

Stocking, on the other hand, is a relative measure of the degree of site occupancy with due regard to the objectives of management, and it is often expressed as a percentage of full site occupancy. At a certain stage of its development a stand may be well stocked for the production of sawtimber. In other words, that particular stand density is well suited to meet the objective of growing timber with dimensions to meet the needs of the sawmiller. That very stand will at the same time be understocked for the production of pulpwood and overstocked for the production of veneer logs. Further, because trees are continually increasing in size, stocking changes over time while stand density in terms of stems per unit area is held constant.

Basal area per unit area of land is commonly used as a quantitative measure of stocking.

The control of stand density through planting at the required spacing and spatial arrangement, suppression of ingrowth, and thinning to allow room for growth is a primary tool of forest management to achieve optimal stocking for a particular crop of trees. A collection of stands that are fully stocked is a prerequisite for the concept of a normal forest.

Determination of Optimal Stand Density

The effects of stand density on growth parameters of trees and stands of trees have been studied intensively. Much of the initial work in this field was based on an extravagant set of 27 installations of field experiments in South Africa, established mainly in the late 1930s, and known as the correlated curve trend (CCT) experiments. The results quantified many of the effects of stand density for the first time and provide an excellent example to illustrate many of the points below. The aim of the CCT experiments was a replicated installation of the experiment on each of a good, an average, and a poor site for 10 tree species grown commercially in each region where that particular species was grown in that country, in order to consolidate all spacing and thinning research. The aims were not fully met in terms of replication but an ambitious research program ensued.

At each installation large plots were established at between eight and 12 different spacings applied at random and a further eight or 10 plots were grown according to a strictly specified thinning regime. To avoid complications induced by seedling mortality and competition from weeds, the different spacings were achieved by planting at a uniform (high) stand density followed by frequent thinnings in advance of the onset of competition. This practice proved to be contentious and the current generation of spacing experiments, known as the standardized sample size (SSS) CCT experiments, does not employ it.

The premise behind the CCT experiments was that, apart from accident and disease and factors such as grass competition and differences in exposure, the following hold true:

1. In any given locality the size attained by a tree of a given age must be related to the growing space previously at its disposal; all other factors influencing its size are fixed by the locality.
2. Trees planted at a given (stand density) will, until they start competing with each other, exhibit the absolute or normal standard of growth for the species and locality. (In the original publication the term stocking was incorrectly used to denote stand density and in this section it is replaced by stand density within parentheses.)
3. Trees planted at a given (stand density) and left to grow unthinned will exhibit the absolute or normal standard of growth for the species, locality and the particular density of stock in question.

The first results from the CCT experiments in five pine species, based on observations when the oldest trees were 9 years old, were published in 1947. These early results were 'remarkable and, in a sense, unexpected.' The conclusions drawn were:

1. The age at which competition commences for a stand of given (stand density) is independent of species, site, or climate.
2. The degree of competition (using diameter at breast height (dbh) increment as index) is the same for a given age and (stand density) irrespective of species and site.
3. As (stand density) decreases, dbh and mean height increase; total volume at first increases and then decreases.

The experiments referred to in these conclusions were established under widely different climatic and site conditions by different people. Data were collected by nine research officers independently of each other (due to staff changes during World War II) and yet final thinnings in advance of competition were completed in all experiments within a few months of each other.

With hindsight, it is apparent that some licence was taken. The conclusions applied to five particular pine species as originally no other genera were tested. What was considered to be a poor site in the 1930s would be viewed differently today. Afforestation has spread into marginal areas where the sites are poorer and certainly drier and modern site amelioration techniques make afforestation of sites originally classified as 'poor' quite 'average.' The conclusions being considered 'independent of species, site or climate' thus applied to a fairly narrow range of conditions.

In the CCT experiments all treatments were allocated to plots at random with some restrictions in order to group plots of similar size.

Stand density has also been studied with systematic designs. The circular (wagonwheel) designs known as Nelder experiments (**Figures 1–3**) address either changes in growing space or changes in the shape of the growing space available to the tree in separate installations. In the former case trees are planted progressively further apart along the 'spokes' of an imaginary wheel, with the result that each position further from the hub of the wheel outwards represents a lower stand density while the shape of the growing space is maintained as essentially square. In the second case the trees are planted progressively closer together along the spoke, resulting in growing spaces that vary from square near the hub to spaces with increasing rectangularity the further the location is from the hub.

The 'Scotch plaid' experimental design is based on a rectangular grid and incorporates both increasing growing space and increasing rectangularity of growing space in each installation (**Figure 4**).

Many other experimental designs have been used around the world.

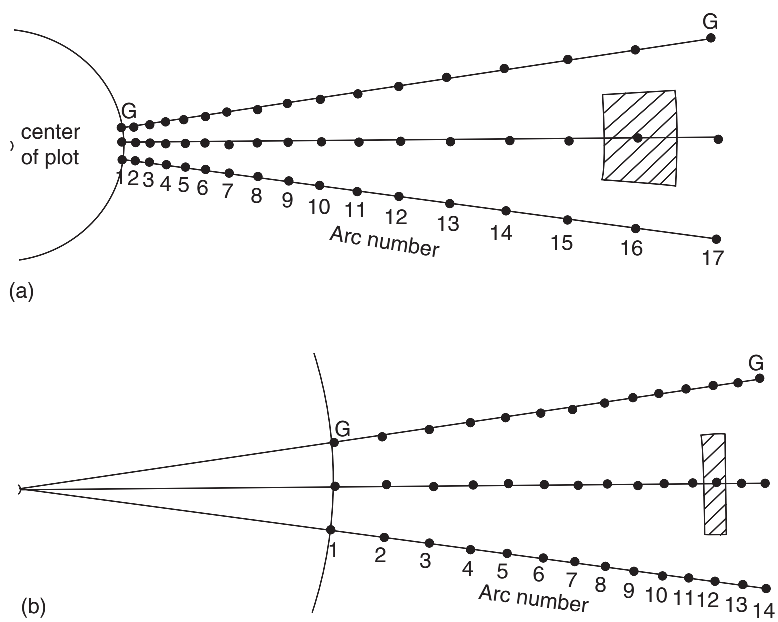

Figure 1 Nelder experiments: effects of design on shape of growing space: (a) square spacing and (b) rectangular spacing. Cross-hatched areas show the nominal growing space available to the tree. Source Reukema DL and Smith JHG (1987) Development over 25 years of Douglas Fir, western hemlock and western red cedar planted at various spacings on a very good site in British Columbia. *USDA Forestry Services Research Paper* PNW-RP-381.

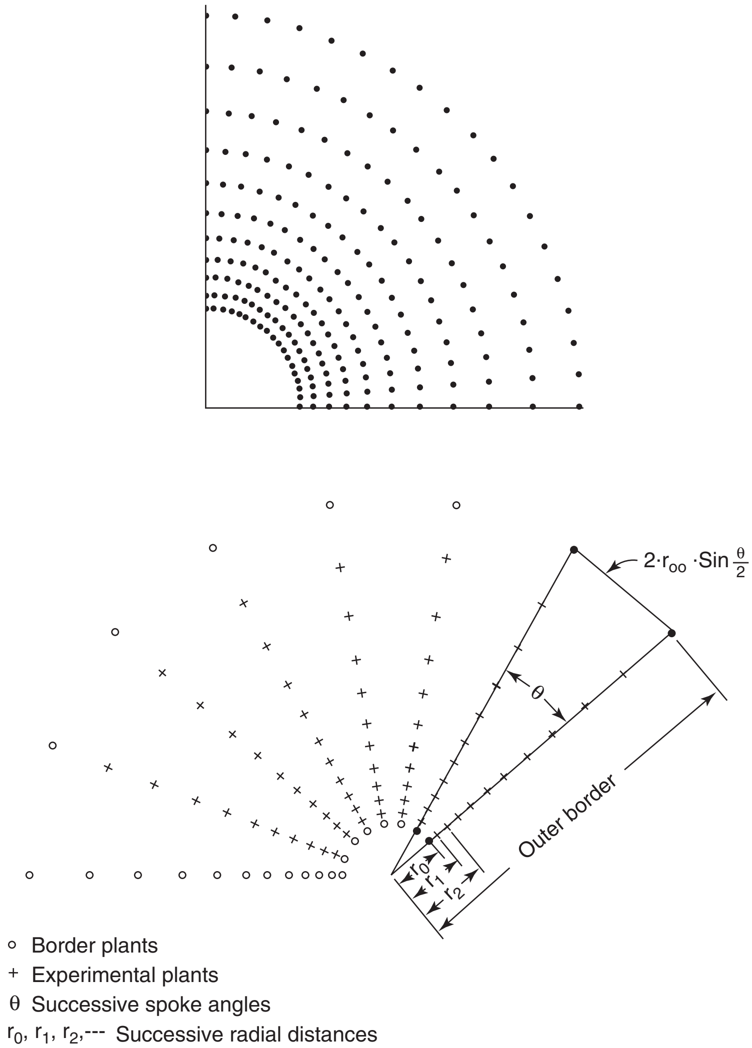

Figure 2 Nelder experiments: segments of variable-density plots (design 1a). Source: Nelder JA (1962) New kinds of systematic designs for spacing experiments. *Biomerics* **18**: 283–307 (top) and Namkoong G (1966) Applications of Nelder's designs in tree improvement research. In: *Proc. 8th Southern Conf. on Tree Improvement*, pp. 24–27. June 16–17 1965. Savannah, Georgia (bottom).

The Effects of Changing Growing Space on Trees

An increase in growing space results in an increase in dbh. Even if trees were grown at a high stand density that resulted in a reduced dbh, a thinning will result in an increase in dbh increment. The rate of that increase depends on the degree of suppression prior to the release (**Figure 5**). This effect is also observed in stands where stand density was reduced by competition-induced mortality.

The height of an individual tree is less affected by stand density than it is by site quality. However, tree height is not unaffected by stand density, and across a range of stand densities there is one that will be optimum for height growth of a particular species. Stand density that is too high or too low will impact negatively on height growth but within the limits of stand density used in plantation forestry there is essentially no effect on top or mean height.

Because stand density has a marked influence on dbh and a minimal influence on height, it has a marked influence on stem taper. The higher the stand density, the less the taper will be.

Increasing stand density results in a decrease in the diameter and length of branches and in some species there is also a decrease in the number of branches per unit length of the tree bole.

The higher the stand density, the poorer stem form will be. Trees grown under conditions of suppression tend to be more crooked than those that are free-growing and there is some evidence that the proportion of trees that are forked will also increase with increasing stand density. However, some species, such

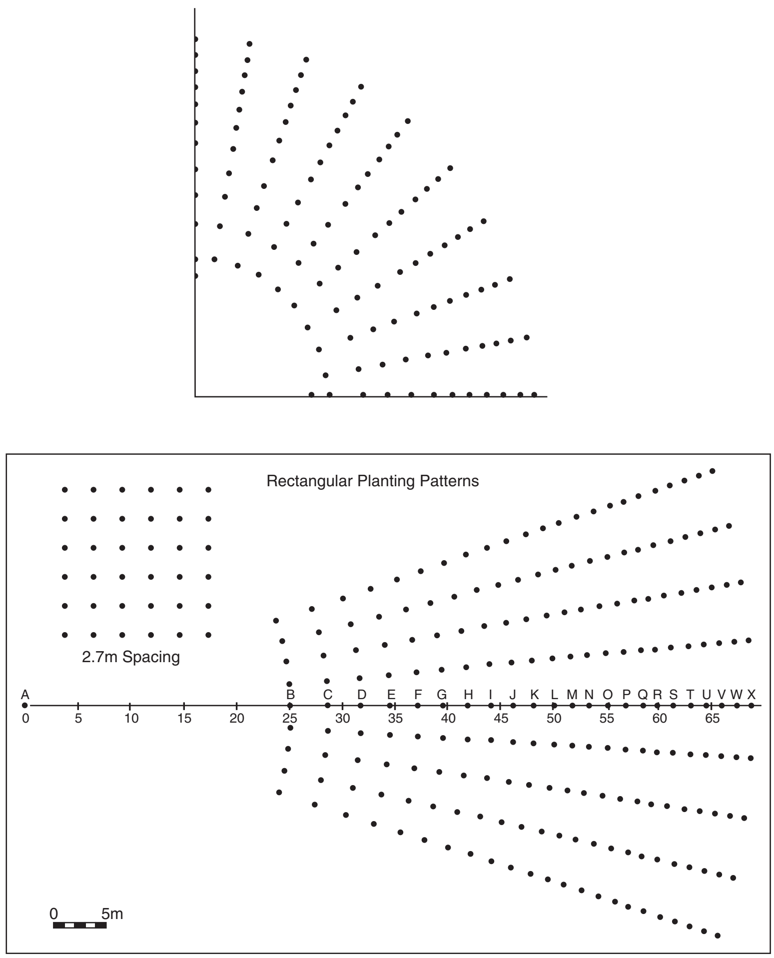

Figure 3 Nelder experiments: segments of variable-density plots (design 1b). Source Nelder JA (1962) New kinds of systematic designs for spacing experiments. *Biometrics* **18**: 283–307 (top) and Bredenkamp BV (1982) Rectangular espacement does not cause stem ellipticity in *Eucalyptus grandis*. *South African Forestry Journal* **120**: 7–10 (bottom).

as *Acacia melanoxylon* and *A. auriculiformis*, must be grown at high stand densities to avoid crook.

As a reduction in stand density increases diameter growth, the proportion of early or spring wood is increased, resulting in a reduction in timber density. There is little evidence to support the popular belief that this results in a reduction in timber strength or quality. Attempts of foresters to reduce the size of the juvenile core through reduced planting spacing and delayed first thinning generally fail to reach their objective. However, in the case of *Pinus patula* where the juvenile core may consist of as many as 20 annual rings, delayed thinnings can restrict the size of the juvenile core.

The Effects of Changing Growing Space on Stands of Trees

As stand density has such a marked impact on the dbh of the individual tree it also has a major impact on stand mean dbh. Mean dbh is controlled almost exclusively by stand density.

High stand density results in an increase in the variation of dbh. Dbh distributions are most uniform when stand density is low and most heterogeneous under conditions of suppression.

If mean height of a stand is defined as the height of the tree with average dbh (mean cross-sectional area), then mean height is affected by stand density because of the influence on dbh. Top height, which can be defined in many ways, is less affected. Top height is sometimes considered to be unaffected by stand density and is thus used to express site quality as the top height of a stand at a given index age; however, at extremes of stand density, top height is also affected.

As stand density controls dbh and affects height, the most important variables determining tree volume, stand density has a major effect on stand volume. If the object of management is merely the production of fiber, then the optimum stand density

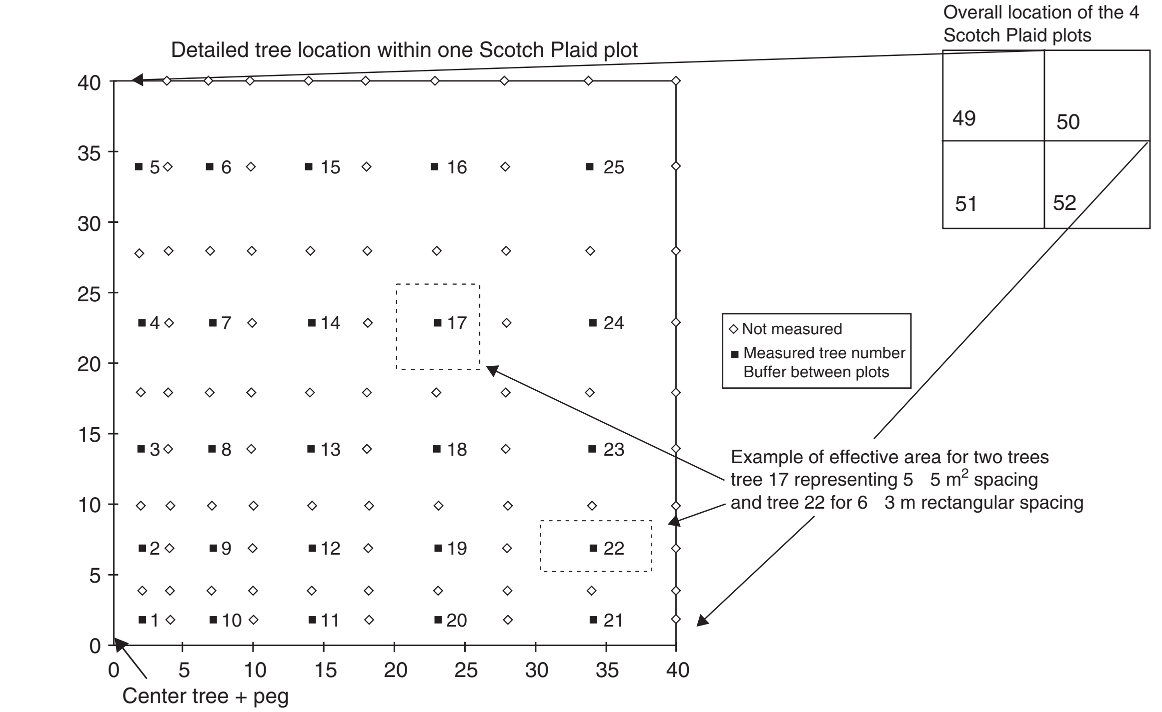

Figure 4 Layout of the 'Scotch plaid' design spacing plots. Reproduced with permission from Gerrand AM and Neilson WA (2000) Comparing square and rectangular spacings in *Eucalyptus nitens* using a Scotch Plaid design. *Forestry Ecology and Management* **129**: 1–6.

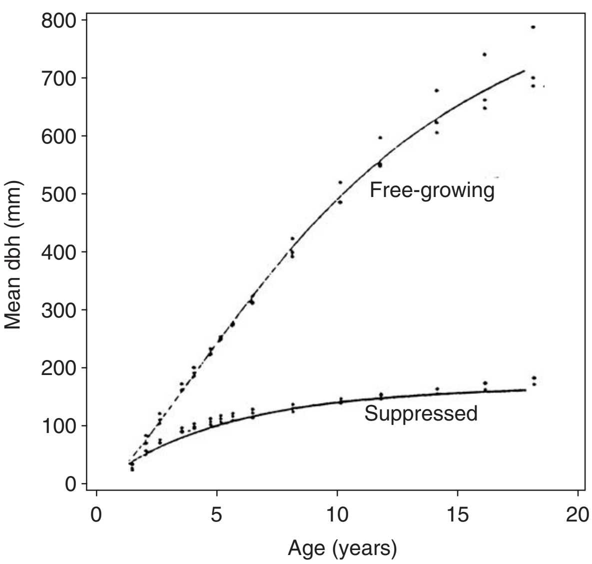

Figure 5 Diameter development of free-growing and suppressed stands of *Eucalyptus grandis* in Zululand. Note the second inflection in the trend amongst the suppressed trees. Source: Bredenkamp BV and Burkhart HE (1990) Diameter growth of *Eucalyptus grandis* under conditions of extreme suppression. *New Zealand Jourrnal of Forestry Science* 20(2): 162–167.

is the highest stand density the site can support without inducing mortality due to competition. However, if a specific crop is being cultivated, there will be an optimum stand density for that crop and that optimum will be at a much lower level than in the case with production of fiber.

The Effects of Rectangularity of Growing Space

The effects of rectangularity of the growing space, measured as the ratio of the distance between rows to the distance between the trees within the rows, on the volume production of trees and stands is negligible, if any. Between-row spacing of as much as six times the within-row spacing has been shown to have essentially no effect on the growth or the shape of the cross-section of the bole. There are however effects on branching. In general, branches oriented with the row curve away from competing branches from adjacent trees and grow towards clear space between the rows. No influence of rectangularity of growing space on the number of branches has been reported.

Spacing and Stocking Practices Around the World

Initial stand densities have been markedly reduced since the 1970s. The wider initial spacings are mainly due to increasing availability of genetically improved planting stock; better site preparation, planting, and tending; improved forest protection, and the advantage of enabling shorter rotations.

Practices differ very widely among countries. In some cold temperate countries trees are planted at 10 000–18 000 trees ha^{-1}. In the UK most conifers are now planted at densities of 2500 stems ha^{-1} whereas in the 1930s about 4500 stems ha^{-1} were planted. In southern-hemisphere countries it is now normal to plant between 600 and 1100 stems ha^{-1} where high-quality sawn timber is produced. Where pulpwood, poles, firewood, or mining timber are required, stand densities are up to 2000 stems ha^{-1}. *Populus deltoides* grown for matches is often established at 400 stems ha^{-1}. Initial stand densities of less than 400 stems ha^{-1} are mainly found in agroforestry situations.

When Very Close and Very Wide Spacings Are Used

The general goal of initial spacing is to provide sufficient trees from which eventually to select a final crop of evenly spaced and acceptably formed trees, within the restraints of site and other factors. For a given spacing, growth responses are heavily dependent on species and site factors.

Appropriate initial spacings and thinnings enable foresters to achieve the end-use objective. For the production of small-sized timber such as pulpwood, poles, and mining timber, volume production in a stand must be maximized, i.e., initial spacing is relatively close and no thinnings, or only light thinnings, are required. For the production of sawtimber and veneer, initial spacings are wider and heavy thinnings are required to produce final crop trees with big diameters in a relatively short time.

Initial spacings are generally relatively wide for fast-growing species of good tree form, where tree establishment costs are high. In the case of *P. deltoides* grown for matchwood, where minimum sizes for peeling preclude the use of timber for thinnings, initial spacings are even up to 5×5 m. Other factors to consider are mechanization, water run-off required by downstream users, and susceptibility to diseases and pests that increase with an increase in stress on trees.

Improved genetics and good silvicultural practices have reduced the need for high initial stand densities. However, where young trees are exposed to severe winds, wide spacings increase the incidence of wind damage. New Zealand evidence suggests that initial stand density of *Pinus radiata* should not be less than 600 stems ha^{-1} to ensure adequate mutual protection.

The appropriate stand density after a thinning depends largely on the amount of foliage a given species can support on a given site. The residual basal area may vary from 9 to 40 $m^2 ha^{-1}$ with higher stand densities with evergreens, shade-tolerant species, and good sites. On sites that are so poor that the root systems compete severely but crowns cannot close, stand densities should be exceptionally low.

Effects of Spacing on Site Capture

When trees are free-growing and not competing with each other, diameter growth is less than the maximum possible. As basal area increases, competition sets in amongst trees, but total growth per hectare continues to increase, although at a decreasing rate until the maximum growth is reached, i.e., the site is fully utilized. With further increases in stand density, the stand increment remains similar over a wide range of stand densities. Therefore, individual trees grow slower in diameter as stand density increases. When competition is so severe that trees lose vigor and become more prone to disease and insect attack, increment becomes less than the maximum.

During the first year or more after establishment of a plantation, when the trees are small, the site is not fully utilized. Only later do roots and crowns spread sufficiently to compete with neighboring trees for light, moisture, and nutrients.

In even-aged monocultures a site can support only a certain number of trees of a given species and size. The maximum number of trees that can be carried decreases with age as the trees grow larger, rapidly at first but slowly towards the end of the rotation. On dry and infertile sites, competition amongst trees will occur before their crowns start to compete for light. Where soil moisture and nutrients are in abundance, competition for light may set in before the roots are in severe competition.

The most vigorous trees are most likely to survive the competition, i.e., the tallest are generally the largest in all dimensions. The weaker trees become increasingly suppressed and eventually die. This process is called natural thinning. In very dense stands, competition is so severe that dominant trees also grow slower. This can be avoided by timely thinnings.

The trees of monoculture plantations are generally uniform in spacing and size and therefore also in vigor. Either their crowns or roots will start to compete rather suddenly and then or soon afterwards will be the ideal time for the first thinning. The initial spacing should preferably be wide enough so that the trees to be thinned will have grown to merchantable size.

The earliest a plantation can be thinned without loss of increment varies with the rate of growth, which is determined by site quality, initial spacing, genetics, and intensity of silvicultural practices. It can be as early as age 2 years for *Tectona grandis* planted at 2×2 m in the tropics. In the UK it varies from 20 to 35 years for most conifers, but can be more than 50 years in colder climates.

If the thinning cycle is very long, thinnings are generally heavy and the site may not be fully utilized for some years after a thinning.

Thinning weight, i.e., the number of stems, or basal area, or volume per ha removed during a thinning, expressed as a percentage of the main crop before thinning, is generally between 20% and 60%. Lighter thinnings are regarded as uneconomical. Heavier thinnings leave stands more prone to wind damage and unacceptable increment due to incomplete site utilization.

The most beneficial silvicultural regime for a stand would include frequent light thinnings. These are economically not justifiable. The frequency and intensity of thinnings are thus driven more by economics than good silviculture. However, end-use potential and wood quality also play a role.

Spacing in Agroforestry, Tanbark and Biomass Plantings and Other Unconventional Stands

Spacing is manipulated to produce material which will best meet the market demands and also yield optimal profits. In all forestry stands, including agroforestry, crops are usually thinned or clearfelled before competition becomes so severe that mortality sets in.

In agroforestry, tree seedlings are often planted at the same time as food crops. Spacing between tree rows is often wider than in monoculture plantations to delay the shading of the food crop or forage grown for grazing by the trees. Trees may also be thinned and pruned so that food cropping can continue beyond the tree establishment stage.

In some agroforestry systems trees are planted in strips to provide shade or shelter to the agricultural crops or animals grazing among the trees. Such plantings may occupy less than 5% of scarce farmland.

In alley cropping, nitrogen-fixing shrubs and trees are grown in wide rows to allow cultivation of four to six rows of food crops in between. Spacing between trees varies from less than 2 m to as wide as 5 m.

In semiarid areas as few as 20 trees ha^{-1} are planted where annual crops are grown. Partial shade conditions are sometimes also created in moist areas where perennial agricultural crops, e.g., tea and coffee, are grown, by planting 50–200 trees ha^{-1}.

For woodlots, initial spacing between trees is normally closer than for commercial plantations. On good sites, trees grown for firewood may be planted as close as 1×1 m and if grown for poles at 2×2 m, to maximize yields. Rotations are typically only 3–6 years.

Acacia mearnsii plantations grown for the production of tanbark are planted at 2200 trees ha^{-1}. When established by means of direct sowing or natural regeneration, many thousands of seedlings ha^{-1} must be removed in one to three successive thinnings to retain 1200–1600 stems ha^{-1} until clearfelling at ages 8–12 years.

In recreational areas, soils are often compacted by the many visitors, thus placing stress on the trees. Therefore, spacing between trees should be wide to minimize competition amongst them.

How Spacing Interacts with other Establishment Practices (e.g., Plowing, Drainage)

The spacing at which trees are planted in plantations is usually determined accurately. For practical reasons, e.g., mechanized operations, locating young trees when weeding, and for line thinning, rows should be straight. Likewise, when natural regeneration is used, respacing or precommercial thinning should be done so that the remaining trees are in rows. Where plantations are established on level, stone-free ground, straight lines can often be seen in a number of directions. However, on many sites it is difficult to achieve precision because of steep slopes, rocks, and old stumps.

Costs of some forestry operations, e.g., weeding and extraction of thinnings, can be reduced by using tractor-mounted equipment and other big machinery. It is therefore sometimes desirable to have rectangular spacings that allow enough space between rows to accommodate such machines. For example, instead of planting approximately 1200 trees ha^{-1} at a spacing of 2.9×2.9 m, the distance between the rows can be increased to 3.5 m and the distance between trees in the row reduced to 2.4 m to maintain the same number of trees per hectare.

Weeds are likely to be suppressed more rapidly in closely spaced stands because of quicker canopy closure. However, this should not be the major objective of close initial spacings because the additional costs of establishing more trees usually far exceed the savings incurred on weeding operations.

After a number of coppice regenerations in *Eucalyptus* plantations for example, reestablishment with nursery-raised plants is usually necessary. It is then preferable to plant in the rows of the killed stumps rather than between the rows, to enable easy future access, e.g., for firefighting.

Use of Thinnings to Manipulate Stand Density and Achieve Optimal Stocking

Artificial thinning is the removal of a proportion of individual trees from a stand before clearfelling. It is generally understood to take place after the onset of competition. However, precommercial thinnings may take place before trees start to compete with each other. Thinnings are mostly prescribed as stems ha^{-1} or basal area to remain at a given age.

In stands that are to be thinned, more trees are established than the required final crop, mainly to ensure sufficient trees from which the final crop can be selected, but also to utilize the site better.

The main objectives of thinnings are to:

- provide the remaining trees more space for crown and root development to encourage stem diameter increment and thus reach the desired size sooner
- remove trees of poor form so that final crop trees are of good quality
- manage relatively uniform growth in order to enhance wood quality and sound end-use potential
- prevent severe stress that may induce pests, disease, and stand instability
- provide an intermediate financial return from sales of thinnings.

Thinning schedules are therefore based on both biological and economic considerations. Skillful thinning can increase economic yields although the site is not fully utilized throughout the entire rotation, because veneer and sawlog prices generally increase significantly with increased log diameters.

An infinite number of combinations is possible between initial spacing, timing and intensity of thinning, final density, and rotation length. A unique thinning regime is therefore possible to fit every case of management and market circumstances.

See also: **Afforestation**: Stand Establishment, Treatment and Promotion - European Experience. **Inventory**: Stand Inventories. **Plantation Silviculture**: Short Rotation Forestry for Biomass Production. **Silviculture**: Coppice Silviculture Practiced in Temperate Regions; Unevenaged Silviculture.

Further Reading

Avery TE and Burkhart HE (1994) *Forest measurements*, pp. 287–296. New York: McGraw-Hill.

Bredenkamp BV (1982) Rectangular espacement does not cause stem ellipticity in *Eucalyptus grandis*. *South African Forestry Journal* 120: 7–10.

Bredenkamp BV (1984) The CCT concept in spacing research. In: Grey DC, Schönau APG, and Schutz CJ (eds) *Proceedings of the IUFRO Symposium on Site and Productivity of Fast Growing Plantations*., vol. 1, pp. 313–332. Pretoria and Pietermaritzburg, South Africa: Stellenbosch University Press.

Bredenkamp BV (1990) The Triple-S CCT design. In: Von Gadow K and Bredenkamp BV (eds) *Management of* Eucalyptus grandis *in South Africa*, pp. 198–206. Stellenbosch, South Africa: Forest Mensuration and Modelling Working Group.

Bredenkamp BV and Burkhart HE (1990) Diameter growth of *Eucalyptus grandis* under conditions of extreme suppression. *New Zealand Journal of Forestry Science* 20(2): 162–167.

Clutter JL, Fortson JC, Pienaar LV, Brister GH, and Bailey RL (1983) *Timber Management; A Quantitative Approach*, pp. 64–65, 68–83. New York: John Wiley.

Evans J (1992) *Plantation Forestry in the Tropics*, pp. 38–46, 217–266, 285–303. Oxford: Clarendon Press.

Gerrand AM and Neilson WA (2000) Comparing square and rectangular spacings in *Eucalyptus nitens* using a scotch plaid design. *Forestry Ecology and Management* 129: 1–6.

Hammond D (1995) *Forestry Handbook*, pp. 83–89. Christchurch, New Zealand: New Zealand Institute of Forestry.

Lewis NB and Ferguson IS (1993) *Management of Radiata Pine*, pp. 201–240. Melbourne: Inkata Press.

Namkoong G (1966) Applications of Nelder's designs in tree improvement research. In: *Proc. 8th Southern Conf. on Tree Improvement*, pp. 24–27. June 16–17 1965. Savannah, Georgia.

Nelder JA (1962) New kinds of systematic designs for spacing experiments. *Biometrics* 18: 283–307.

Reukema DL and Smith JHG (1987) Development over 25 years of Douglas Fir, western hemlock and western red cedar planted at various spacings on a very good site in British Columbia. *USDA Forestry Services Research Paper* PNW-RP-381.

Savill P, Evans J, Auclair D, and Falck J (1997) *Plantation Silviculture in Europe*, pp. 139–161. Oxford: Oxford University Press.

Shepherd KR (1986) *Plantation Silviculture*, pp. 236–262. Dordrecht: Martinus Nijhoff.

Smith DM, Larson BC, Kelty MJ, and Ashton PMS (1997) *The Practice of Silviculture: Applied Forest Ecology*, pp. 69–130. New York: John Wiley.

Van Laar A and Akca A (1997) *Forest Mensuration*, pp. 165–173. Göttingen: Cuvillier Verlag.