See also: **Harvesting**: Roading and Transport Operations; Wood Delivery. **Operations**: Forest Operations Management.

Further Reading

Bowersox D and Closs D (1996) *Logistical Management: The Integrated Supply Chain Process*. New York: McGraw-Hill.

Harstela P (1993) Forest work science and technology, part 1. *Silva Carelica* 25: 51–93.

Harstela P (1996) Forest work science and technology, part 2. *Silva Carelica* 31: 125–136.

Karanta I, Jokinen O, Mikkola T, Savola J, and Bounsaythip C (2000) Requirements for a vehicle routing and scheduling system in timber transport. In: Sjöström K (ed.) *Logistics in the Forest Sector*, pp. 235–251. Helsinki: Timber Logistics Club.

Linnainainma S, Savola J, and Jokinen O (1994) EPO: A knowledge based system for wood procurement management. In: *7th Annual Conference on Artificial Intelligence*, Montreal, pp. 107–113.

Winston WL (1997) *Operations Research: Applications and Algorithms*, 3rd edn. Belmont, CA: Duxbury Press.

Nursery Operations

K McNabb, Auburn University, Auburn, AL, USA

Introduction

Forest regeneration is the very foundation of sustainable forestry. While many forests are regenerated using natural techniques, increasing annual wood harvests will depend upon plantation forestry. Moreover, planting is necessary for afforestation on degraded lands, abandoned agricultural lands, or anywhere that trees are to be reintroduced without a natural seed source. According to the most recent Food and Agricultural Organization (FAO) Forest Resource Assessment, there are close to 4.5 million ha planted each year. If one assumes that planting area is also a reflection of nursery production and using an estimated average spacing of 3×2 m (1666 trees ha^{-1}), this is an annual nursery production of 7.5 billion seedlings. Asia has the largest planting area with 62% of the world total, followed by Europe with 17%. Pines occupy 20% of all plantations worldwide, other conifers 11%, and eucalyptus 10%. The stock used for planting these areas almost invariably come from forest tree nurseries. Nursery managers are responsible for producing a seedling of suitable quality in a reasonable amount of time at a reasonable cost, which can withstand the rigors of processing, storage, transportation, planting, and what is more likely as not, harsh environmental conditions. If the stock does not survive, more is lost than just the cost of the planting stock. Also forfeited may be the cost of preparing the site, growth forfeited until the next planting date, and the expenses incurred if additional weed control, fertilization, or other cultural practices must be conducted. These costs may be, and usually are, substantially greater than the cost of planting stock. It is no wonder that organizations dependent upon successful plantation management consider nursery operations to be the heart of their regeneration program.

As a general rule, there are two types of planting stock – bareroot and container. The decision to rely on bareroot or container technology depends upon many factors. Certainly the physiological requirements of the species is tantamount in importance. Certain genera, such as *Eucalyptus*, are invariably grown in containers and survive poorly when planted bareroot. Other genera, such as the pines, are commonly produced bareroot. Even so, certain pine species, particularly those in the tropics (e.g., *Pinus caribaea)* require containerization. Boreal species may be containerized to shorten their time in the nursery. Whereas producing plantable bareroot stock may take 2–3 years for some boreal species, the environment of container production can produce smaller planting stock in far less time. The ability to control the growing environment is also important when producing vegetatively propagated material which is high in value and/or may require more exacting conditions to root and/or develop. Finally, planting adverse (droughty) sites may require the use of containerized stock. A possible disadvantage to containerization is a substantial increase in cost. In the southeastern United States, for example, the price of container grown stock is generally four to five times higher than the same species grown bareroot. Container stock is also more expensive to transport.

Bareroot Production

Site and Facilities Requirements

The selection of a good site is of paramount importance to the efficiency of a bareroot nursery. The most important characteristics are soil texture and water quality. Only a few decades ago, a medium textured soil was generally considered a requirement for a good bareroot nursery site. Older nurseries tend to be found on loams and silt loams. These soils, however, are not always conducive to using machinery during the wet season which is also frequently the planting season when seedling harvesting must take place. Sandy soils are preferred for bareroot nurseries as for the most part they can be better worked during wet seasons without damage to soil integrity, machine use is more efficient, and equipment may re-enter a field sooner after a rain. Slope to insure efficient yet low energy water flow is a requirement. Slopes of around 0.5% (50 cm over 100 m) are generally considered ideal. When constructing a bareroot nursery, topsoil is usually removed from the site, and the site leveled using modern techniques. The topsoil is then redistributed over the site for a final grading.

Water availability, both in terms of quality and quantity, is essential to bareroot nursery management. There is little a manager can do if the water supply, be it underground or surface, is only seasonally available or of insufficient quantities. Perhaps the most commonly overlooked of these two factors is that of water quality. Managers tend to look for the quantity of water and often forget to check the quality. Extremes of pH, particularly alkaline water with high salt contents, will greatly increase the difficulty of producing quality bareroot seedlings. A simple chemical test will determine if there are hidden problems in the water supply.

The physical facilities normally required for a bareroot nursery are: office and managerial space including a space for nursery workers to meet and eat, an area for seedling processing, a seedling cold storage facility including a truck loading area, sheds for equipment and machine storage, equipment maintenance shop, pesticide storage and mixing facility, irrigation pumping station, and a seed storage unit, with the size of each of these components depending upon seedling production goals. Seedling cold-storage units are typically built to store millions of seedlings with easy loader access and maneuverability. Although this is expensive space, larger seedling storage units allow the nursery manager more flexibility in the harvesting process. As long as seedlings can be stored, the manager can make use of good weather and labor availability by lifting seedlings. Another facility that deserves considerable thought is the pesticide storage and mixing facility. These are specialized structures that may have special legal requirements regarding their construction. Specific airflow volumes, shelf spacing, spill containment, backflow prevention, and other safety specifics should be considered.

Soil Preparation and Sowing

A typical sequence of ground preparation for bareroot production is; subsoiling, plowing and/or harrowing, and bed shaping (**Figure 1**). Subsoiling is usually done with a 3 to 5 shank agricultural

Figure 1 *Pinus radiata* in a bareroot nursery in Chile. Bareroot stock is typically produced on a large scale in raised beds with several rows per bed. In this particular case, the plants originated from cuttings planted directly in the bed. Most bareroot stock, however, is produced by sowing seed.

implement to a depth of 40–60 cm. Many nursery managers will subsoil in perpendicular directions across their fields. Depending upon soil type and previous crop, the site should be turned with a plow or simply harrowed to incorporate and chop plant materials, aerate the soil, and break up soil clods. The bedding plow is then used to shape and level a bed, usually 120 cm in width and approximately 20 cm deep. Alleys between beds are typically the width of one tractor tire, around 40 cm. The number of beds per irrigation unit varies but is selected in function of the irrigation system. The life blood of the nursery is water, with the irrigation system consisting of a network of pumps, pipes, controls, and sprinklers. Most modern bareroot nursery irrigation systems are removable to facilitate soil preparation. Field pipes may be laid out and connected anytime after subsoiling, to facilitate bed layout.

Sowing in bareroot nurseries may be done using machines, or by hand, with species usually the determining factor. Fairly sophisticated tree seed sowers have been developed. Commercially available vacuum sowers are adjustable to seed size and spacing. Such sowers usually provide more control of within-row seed placement and theoretically result in a more uniform spacing for individual seedlings, producing a more uniform crop. Other common sowers dribble the seed along a furrow in the bed in a semicontrolled rate. In either case, the seed are pressed into the soil by a roller following seed placement. In many cases, however, particularly for very large seed or very small seed, hand-sowing is still the typical sowing method. After sowing, bareroot seedbeds are mulched to protect the soil surface from rain impact and maintain bed integrity. Although chemical soil adhesives are used with common success, many nursery managers prefer organic materials such as bark or other by-products from fiber processing that have the other advantages of helping maintain seedbed moisture and contributing to soil organic matter content.

Controlling Morphological Development

Seedling spacing has a tremendous impact on individual seedling development. Larger seedlings survive and grow better after outplanting and are more expensive to grow, but might reduce overall reforestation costs. Seedbed spacing, therefore, is a compromise between production costs and seedling size/quality. Spacing is also species dependent, although as a general rule pine are sown with a seedbed density target of around 150 to 300 seedlings m^{-2}. Hardwood spacings generally require more bed space for production, but again this is species specific. Seedbed density targets may typically vary from 50 to 150 m^{-2}.

Application of the major fertilizer elements of nitrogen, phosphorus, and potassium is almost always necessary to produce seedlings of suitable size within a reasonable time-frame. Fertilizer applications should be based on a soil chemical analysis and professional recommendations supported by empirical observations. Phosphorus and potassium may both be applied to the soil at the time of harrowing. Nitrogen is generally applied over the top of seedlings, either in liquid or granular form, beginning 1 to 2 months after germination. Most species respond well to nitrogen and fairly significant amounts of this element (100–200 kg ha^{-1}) may be applied to nursery beds. Because large amounts of nitrogen are used in bareroot production and because nursery soils are often well drained, nitrogen use efficiency and loss through leaching may be a concern to nursery managers. Micronutrients can be important in specific cases depending upon local soil conditions. Micronutrients are typically applied in a liquid spray. Soil organic matter maintenance is a variable that profoundly affects soil quality and nutrition management. Other than organic matter additions and seedbed mulching, nursery managers typically follow a rotation of 1 or 2 years of seedling crops with 1 or 2 years of cover crops in order to increase or maintain soil organic matter levels as well as a possible reduction in soilborne disease populations.

Top-pruning and root pruning may be used to manipulate morphological development of planting stock. Top-pruning involves the removal of the top of the seedling using a rotary or shearing blade. The primary objective of this treatment is usually to slow the growth rate of the crop. An anticipated secondary benefit is increased crop uniformity resulting from allowing smaller (unpruned) seedlings more of an opportunity to catch up to the larger (pruned) seedlings. An even more severe reduction in seedling growth rate can be achieved by undercutting or wrenching seedling root systems. Another important objective of root pruning may be to provide for a more fibrous root system (expanded water absorbing surfaces) and a better root to shoot ratio. Both shoot and root pruning are species dependent and may not be employed in all cases. Transplanting in the nursery, for example, may be a better method to promote a more desirable root to shoot ratio (**Figure 2**).

Pest Control

Weed, insect, and disease pests are serious threats to the production of quality planting stock. Many pests can be controlled through the use of modern

Figure 2 Transplanting Sitka spruce (*Picea sitchensis*) in a nursery in Scotland. Boreal species and temperate conifers are often transplanted in the nursery to improve seedling quality. A 3-year-old tree having been grown for 1 year in a seedbed and 2 years in a transplant bed is known as 1 + 2 stock. Subtropical and tropical species are rarely transplanted in the nursery and are usually outplanted to the field as 1 + 0 stock.

pesticides. Even so, constant vigilance is necessary on the part of the nursery manager as significant losses to pests can occur in a relatively short time. Nursery herbicides include oxyfluorfen, napropamide, glyphosate, and sethoxidim, to name a few. Both oxyfluorfen and napropamide are pre-emergence compounds, while glyphosate is a postemergence compound used as a directed spray. Sethoxidim is active against grass species only and with appropriate caution may be used over the top of most species. Cost-effective herbicides tremendously impact seedling cost and quality. An integrated pest management program should be employed for insect and disease pest control. Careful almost daily monitoring of pest levels is necessary in nursery operations, with insect and disease pests easily controlled if identified early enough. On the other hand, many nursery managers use prophylactic pesticide applications for soilborne diseases such as damping-off. Soil fumigation prior to seedbed preparation is a common approach in this case. All pesticide use requires a knowledge of the compound, how it works, and any potential environmental impact. It is the ultimate responsibility of the nursery manager to see these compounds are used appropriately.

Seedling Processing

Bareroot seedlings may be harvested by hand or machine. Machine lifting is much more efficient, enabling nursery workers to lift 600–800 thousand pine seedlings per day (spacing $200\,\mathrm{m}^{-2}$) with a crew of fewer than 12 people (**Figure 3**). There are questions, however, as to whether machines may damage the stems and roots of seedlings and therefore decrease seedling quality. After lifting seedlings may be 'graded' (separated into morphologically based classes) or 'culled' (removal of 'nonplantable' seedlings). The decision to grade or cull seedlings has significant influence on the cost of processing. The definition of a 'quality' seedling (i.e., the 'target') is species dependent, and affected by many factors including acceptable seedling cost, environmental conditions at the planting site, and planting method. This is a broad and often debated topic that must be considered by each nursery operation. Upon grading, bareroot seedlings are packaged in one of three ways: boxes, bales, or bags. Both boxes and bags provide a nearly complete seal for seedling storage, while bales protect only the roots and may need watering if stored for several weeks. Water or water-absorbent gels may be sprayed on the roots prior to storage. Cold storage of bareroot seedlings helps reduce the heat of respiration and slows metabolic rate. Storage temperature varies by species with some, particularly boreal species, stored at below freezing temperature, while others are stored at 2–5°C. Storage time before seedling quality is compromised is species dependent and may vary from 1 week to several months.

Figure 3 Mechanical lifting of slash pine (*P. elliottii* Engl.) in the southeastern United States. This nursery produces 1 + 0 bareroot stock that is sown in April (spring) and is lifted 8–10 months later during winter. The machine lifts the entire seedbed in one pass. In this example, packing in bags is done in the field as opposed to transporting to a central processing area.

Container-Grown Stock

Site and Facilities Requirements

There is a great deal more flexibility when selecting a site for a container nursery. Because soil quality has been removed from consideration, a container nursery can be placed at nearly any location where power, roads, labor, and water are available. Many container operations require a reliable semiskilled workforce and labor availability is an important consideration. Water quality, however, is of paramount importance. There is little buffering capacity in the small cells of container-grown plants. Water quality problems may appear and become significant in a relatively short time-frame. In addition, because nursery operations invariably use fertilizers and pesticides, proximity to habitation, streams, or environmentally sensitive areas should be considered.

About the only buildings that are universal to container nurseries are those related to personnel requirements (e.g., administrative, meeting, eating, and restroom locations). Other common structures are a medium preparation and container filling facility and their associated storage spaces for media and containers. The types and requirements of other structures are highly dependent upon the propagation techniques used. Most operations require a seed germination or misting chamber for rooting cuttings. In this case, tight control of water amount, spray droplet size, humidity, and temperature are important (**Figure 4**). Some facilities have heated pads to increase the temperature of the root environment. After the initial seed germination or rooting phase, plants are typically transported to protected plant development areas. These areas may be entirely closed systems, or may be outdoors. Finally, upon reaching a suitable size, the stock is transported or exposed to ambient conditions so they may begin the process of physiological acclimation to planting conditions. Each of these phases may require a specific facility.

Container and Medium

Forest tree seedlings are grown in a variety of containers. In nurseries in many developing nations, small plastic bags filled with subsoil are common. However, most containers used today in modern nurseries are small polyethylene (hard plastic) tubes or styrofoam blocks with cavities. In both situations, the container is reused after cleaning and disinfection. The small tube-type container may be hung in wire or plastic racks at waist height, while styroblocks are typically placed on benches. Both systems should allow roots to air-prune on the bottom. The size of the cavity varies widely but those used for pines and *Eucalyptus* are commonly about 2–4 cm in diameter at the top and 12–18 cm deep, narrowing to a smaller drainage hole at the bottom and ribbed along the length of the cavity to prevent root

Figure 4 A single indoor unit of a container nursery in Sweden. Temperature, humidity, irrigation, and, to some extent, light can be managed in such structures. This speeds up the morphological and physiological development of the plants. Fertilization and pest control is typically done through the irrigation system, which in this case is an overhead traveling boom sprayer.

spiraling. Other than water quality, the container medium is the most important factor contributing to successful container growing. While media are often available commercially, many growers create their own mixtures. Normally, the medium is based on a locally available and abundant organic compost (e.g., pine bark, rice hulls, or other processing residues) that is used alone or mixed with vermiculite, soil, or other materials. These mixtures attempt to provide a well aerated, well drained, disease-free medium, with good water-holding capacity. The correct mixture promotes root growth throughout the medium. Commercially available and 'homemade' machines are used to fill containers.

Starting the Crop

Container stock may originate from seed, germinants, cuttings, and plantlets. Seed may be hand- or machine-sown. Automatic sowers are commonly used for pine and *Eucalyptus*. Whether or not to sow more than one seed per cell depends upon germination percentage, value of the seed, and the availability of labor to thin and transplant. Transplanting may well result in uneven growth between seedlings and the need to segregate later by size. After sowing, seed may or may not be covered depending upon the species and sowing technique. Germinants are produced by germinating seed in special flats or beds and transplanting the young plants (usually with the cotyledons still attached) into the containers. A number of species may be transplanted from specialized seedbeds to containers including species of both the genera *Pinus* and *Eucalyptus*. Usually transplants are shaded and maintained in high humidity conditions until well rooted.

Vegetative propagation through the use of cuttings is increasingly common for initiating container-grown planting stock, particularly for the genus *Eucalyptus* (**Figure 5**). To be successful, such a program depends upon an intensive clonal selection effort which includes research regarding the age, size, location, and season for taking woody plant cuttings for cost effective success. There may be physiological conditioning of the cutting source, the use of rooting hormones, and the posttransplanting environment may require exacting conditions. Large-scale production nurseries must have adequate rooting success if this technology is to be cost effective. Cutting based programs usually manage 'clone banks' or 'clone gardens' as a ready source of superior genotypes used as a source of material.

Container-grown planting stock may also originate from plantlets which are small plants or cuttings produced *in vitro* using various tissue culture methods. Individual clones may be 'stored' in jars in the laboratory and then 'bulked up' according to the requirements of the planting sites. Although not as common as using traditional vegetative propagation

Figure 5 A container nursery in southern Brazil. The majority of these plants are *Eucalyptus* spp. originating from cuttings. After rooting the cuttings in indoor facilities with humidity and temperature controls, the stock is moved outdoors to acclimate to planting conditions. The different colors seen in the photograph are different clones.

techniques based on cuttings, the use of plantlets will undoubtedly become more frequent as biotechnology programs are further developed.

Morphological Development and Pest Control

Fertilization of container-grown stock is done both by adding nutrients to the container medium prior to filling the containers, and as supplemental foliar sprays. Fertigation is particularly appropriate for container-grown technologies, requiring the use of specialized injectors and fertilizer holding tanks. It is imperative that irrigation systems provide even distribution of water over the growing area. In addition, slow-release fertilizers may be effectively added to the container medium, insuring nutrient availability over an extended period of time. A factor of increasing importance relative to container stock fertilization is the ultimate fate of fertilizers (and pesticides) used in the production process. Container operations usually have fast and efficient drainage away from the site. Also, unlike bareroot operations there is no soil medium to hold, transform, or otherwise process fertilizer elements. The result is an increased possibility of chemical movement from the production site. Many container operations now ‘close the system,’ by collecting and reusing water that drains from the seedling racks.

Container-grown stock needs to be segregated by size. For whatever reason, growing medium, seed vigor, transplant shock, or fertilizer distribution, container stock frequently shows remarkable variation in morphological development. Larger plants may be the first sent to the field for transplanting or segregated so that their growth may be slowed through irrigation reduction. Smaller plants may receive additional fertilizer to accelerate their development in order to reach plantable size. Sorting by size is a labor-intensive operation and adds considerably to planting stock cost.

Because container-grown stock is generally produced in soilless media, pest problems tend to be less frequent. Weed control, for example, is greatly reduced and occasional hand-weeding often suffices. Likewise, the protected environment of the greenhouse limits insect pests. The most serious pest problem for container stock is normally disease, particularly those associated with damping-off, although leaf molds such as *Botrytis* and *Cylindrocladium* may quickly become destructive without quick resolution. The high humidity and temperatures often associated with the early stages of container production are ideal for fungal development.

Storage and Shipment

The existence of a functioning soil/root interface provides a great deal of flexibility in the storage of container-grown plants. With protection from desiccation provided by the medium plug and occasional

Figure 6 A truck used for transporting seedlings from the nursery to the field. Note these seedlings are in containers and resting on a stack of specially developed platforms for placement on to the truck.

watering, plants may be stored just about anywhere, including the planting site, for an indefinite period of time. What is gained in storage flexibility, however, is lost in transportation cost, as the amount of space and energy needed for container plant transportation is considerably higher than for bareroot planting stock (**Figure 6**). In addition, because container stock cannot be vertically stacked, specialized transportation structures are required.

Final Considerations

Clonal Technology

The increased used of clonal technology has impacted seedling production in many areas of the globe. Although the decision to use container techniques for planting stock production has generally been mandated by biological and environmental factors in the past, this is changing with the increasing importance of clonal propagation to maximize the benefits of genotypic selections. Whether through tissue culture techniques such as somatic embryogenesis or cutting propagation from clone banks, the production of forestry planting stock is becoming more associated with the 'bulking up' of highly productive genotypes derived from intensive programs of selection and testing. Some genera, *Eucalyptus* for example, easily lend themselves to vegetative techniques necessary for clonal production (**Figure 7**). Others, such as the pines, require a higher economic threshold as they are so cheaply produced in bareroot systems. The continual progress in the science of biotechnology, however, may profoundly influence the economics of planting stock production. If lignin content, disease resistance, or drought tolerance can be introduced into cell lines through such technology, the economics of bareroot versus container grown stock will have to be rethought.

An Integrated Approach

In the past, individuals working in nursery science did not regularly interact with those working in site preparation or weed control. Each was typically viewed as an independent topic. Forestry enterprises, whether investigatory or managerial, were typically organized along these different areas and acted independently of each other. Forest regeneration managers are coming to view plantation establishment as an integrated process. That is, none of the parts in the process is wholly independent of the others. This is important because seedling quality is now mandated by considerations broader than just a 'survivable' seedling. Larger seedlings may compensate for chemical weed control, for example, or planting may take place year-round through the use of irrigation so that nursery and planting operations are seamless and independent of season. Nursery operations directly affect seedling quality, both morphologically and physiologically. Nursery managers can manipulate their product through cultural techniques such as spacing, fertilization, and pruning.

Figure 7 Multiple shoot tips of a *Eucalyptus grandis* and *E. urophylla* hybrid (known as urograndis) produced through tissue culture techniques. Individual clones can be kept in this form and then bulked up to produce indoor 'clonal gardens' which in turn are used to produce planting stock based on cutting technology. Such systems may become much more common with the development of biotechnology science.

It is becoming more recognized that seedling quality interacts with silvicultural techniques used in site preparation and weed control and therefore seedling cost should be evaluated as related to the entire regeneration process. As the forestry research community further investigates this important topic, we may find that nursery techniques are more important to plantation establishment and growth than has been believed in the past.

See also: **Afforestation**: Ground Preparation; Species Choice. **Genetics and Genetic Resources**: Propagation Technology for Forest Trees. **Operations**: Forest Operations Management. **Plantation Silviculture**: Forest Plantations; Tending. **Tree Breeding, Practices**: Genetic Improvement of Eucalypts.

Further Reading

Aldhous JR and Mason WL (1994) *Forest Nursery Practice*, Forestry Commission Bulletin no. 111. London: HMSO.

Chavasse CGR (ed.) (1981) *Forest Nursery and Establishment Practice in New Zealand*. New Zealand Forest Service, Forest Research Institute.

Colombo SJ, Menzies MI, and O'Reilly C (2001) Influence of nursery cultural practices on cold hardiness of coniferous forest tree seedlings. In: Bigras FJ and Colombo SJ (eds) *Conifer Cold Hardiness*, pp. 223–252. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Duryea ML and Dougherty PM (eds) (1991) *Forest Regeneration Manual*. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Duryea ML and Landis TD (eds) (1984) *Forest Nursery Manual: Production of Bareroot Seedlings*. The Hague: Martiinus Nijhoff/Dr W. Junk.

Gonçalves JLM and Benedetti V (eds) (2000) *Nutrição e Fertilização Florestal*. Piracicaba, Brazil: Instituto de Pesquisas e Estudos Florestais.

Landis TD, Tinus RW, McDonald SE, and Barnett JP (1998) *The Container Tree Nursery Manual*, vol. 1–6, Agriculture Handbook no. 674. Washington, DC: US Department of Agriculture Forest Service.

McNabb KL (ed.) (2001) The interaction between nursery management and silvicultural operations. *New Forests* 22(1–2): 1–158.

Rose R, Haase DL, and Boyer D (1995) *Organic Matter Management in Forest Nurseries: Theory and Practice*. Corvallis, OR: Nursery Technology Cooperative, Oregon State University.

South DB (1993) Rationale for growing southern pine seedlings at low seedbed densities. *New Forests* 7: 63–92.

Williams RD and Hanks SH (1994) *Hardwood Nursery Guide*, Agriculture Handbook no. 473. Washington, DC: US Department of Agriculture Forest Service.