# Tropical Nursery Concepts and Practices

Diane L. Haase, R. Kasten Dumroese, Kim M. Wilkinson, and Thomas D. Landis

## Contents

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D.L. Haase (✉)
State and Private Forestry, USDA Forest Service, Portland, OR, USA
e-mail: dlhaase@fs.fed.us

R.K. Dumroese
USDA Forest Service, Rocky Mountain Research Station, Moscow, ID, USA

K.M. Wilkinson
Gibsons, BC, Canada

T.D. Landis
Native Plant Nursery Consulting, Medford, OR, USA

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## Abstract

A tropical nursery produces quality plants by providing a favorable environment and meeting the plants' needs. Nursery propagation structures are designed to mitigate the factors that limit plant growth on a given nursery site. The ideal types of nursery structures are determined by site characteristics, nursery objectives, crop size, species, length of crop rotation, and the number of crops grown per year. Growing medium and container type are also important considerations in crop production. The physical, chemical, and biological characteristics of a growing medium affects seedling health, root development, and growth, and influences nursery operations such as irrigation and fertilization needs. Growers often use different types of growing media for seed propagation, rooting cuttings, and for transplanting larger plants and many mix their own using a combination of organic and inorganic ingredients. The best containers increase seedling root health, encourage good form and shoot-to-root ratios, and lead to good outplanting performance. Different species will require different types of containers based on the types of leaves and root systems they possess.

Sufficient quantities of good-quality water must be available throughout the year to supply all the various uses at the nursery. Irrigation system design and application must meet the needs of a diverse species of plants and cater to their changing needs during different phases in their growth and development. In addition to water, plants require adequate quantities of mineral nutrients in the proper balance for basic physiological processes and to promote rapid growth and development. Nutrition and outplanting performance can also be improved by using beneficial microorganisms such as nitrogen-fixing bacteria and mycorrhizal fungi in the nursery. Providing optimum growing conditions for nursery plants and practicing good hygiene and sanitation in the nursery are important tools to prevent problems with diseases and pests. Many problems are triggered by stresses that can be avoided or corrected by good horticultural practices. Monitoring the crop and keeping records enables early detection and treatment of problems that do arise.

## Keywords

Propagation Environment • Irrigation • Fertilization • Growing Media • Nursery Containers • Beneficial Microogranisms

## Introduction

The nursery environment is a place to start, grow, and protect locally adapted plants until they are healthy, strong, and large enough to meet the challenges of outplanting sites and achieve project goals (Evans 1996). The work nurseries do to produce high-quality plants for reforestation helps perpetuate these species. Good nursery work makes successfully establishing plants more effective, affordable, and more likely to happen, whether nursery clients are foresters, farmers, restoration ecologists, community groups, or others.

Crop growth relies on optimal levels of light, water, nutrients, temperature, humidity, and space in the nursery. These levels are achieved in the nursery through good design of propagation environments, choices of growing media, and use of appropriate container shapes and sizes. Plant care includes water quality and irrigation management, plant nutrition, working with beneficial organisms, and holistic prevention and management of pests and diseases. This chapter includes key concepts and processes for growing tropical plants in nurseries based on proven techniques, practices, and the best science available at the time of this writing. An understanding of some of these concepts and principles will make it easier to operate a nursery successfully, to serve clients, and to meet project objectives in the field.

## Propagation Environments

Many environmental factors influence growth and production of nursery plants. Photosynthesis and transpiration are the primary processes affected by environmental factors. Photosynthesis is the conversion of atmospheric carbon dioxide to carbohydrates in the presence of chlorophyll, the green pigment in leaves, using the energy in sunlight. Photosynthesis is a “leaky” process because, to allow the intake of carbon dioxide, water vapor is lost through pores, or stomata, on the leaf surfaces, a process called transpiration. To maximize the photosynthesis necessary for plant growth, nursery managers must reduce the factors that limit photosynthesis and/or increase the factors that promote photosynthesis, usually accomplished by using propagation environments.

Propagation environments can be as simple as a garden plot where water and fertilizer are applied, or as complex as high-tech greenhouses that also modify all atmospheric factors. Although some species are grown from seeds, others in the same nursery might have to be grown from rooted cuttings. So, a good tropical plant nursery should be designed with various propagation environments in which plants of similar requirements and growth stages can be grown.

### Minimally Controlled Environments

A minimally controlled environment is the simplest and least expensive of the propagation environments. The most common type is an open growing compound.

**Fig. 1** Open compounds, like at this Republic of Palau forestry department nursery, are common in tropical climates (Photo by Tara Luna)

It consists of an area where plants are exposed to full sunlight and is usually nothing more than an irrigation system and a surrounding fence (Fig. 1). Nurseries use open compounds for plant propagation and for areas to expose crops previously grown inside structures to ambient conditions during hardening. Plants can be grown on elevated platforms, benches, or pallets to improve air pruning of the roots, or directly on a layer of gravel (to provide drainage) that is covered with landscape fabric (to control weeds). Irrigation is provided by handwatering, or by sprinklers for smaller containers or driplines for larger ones. The compound usually needs to be fenced to minimize animal damage, and, in windy areas, a shelterbelt of trees around the compound can protect from desiccation and improve irrigation coverage.

Artificial ponds are another type of minimally controlled environment. They are used for growing riparian, coastal, and wetland plants and can be used to provide specific habitats for certain wetland plants, such as saline conditions for plants adapted to coastal habitats. Wetland ponds can be aboveground reservoirs, such as shallow tanks or cattle-watering troughs, or they can be constructed with heavy plastic liners either in an excavated area or at ground level using a raised perimeter. These simple propagation environments require only periodic flood irrigation; nutrients are often added as controlled-release fertilizer mixed with the medium or through the use of organic-based medium (described below).

## Semicontrolled Environments

Semicontrolled propagation environments modify only a few of the limiting factors in the ambient environment, such as heavy rains, wind, or excessive temperatures. Cold frames are the most inexpensive semicontrolled propagation structures and are easy to build and maintain. Because conditions inside can stay relatively warm and moist, cold frames can be used for seed germination or rooting cuttings. The cold frame needs to be built so that it is weather tight and so the top can be opened daily to allow for ventilation, watering, and the easy removal of plants. The cover must be able to be attached securely to the frame to resist wind gusts. Heavy plastic film is an inexpensive covering but usually lasts only a single season. Hard plastic or polycarbonate panels are more durable and will last for several years; recycled windows work well too. In the tropics, cold frames usually need to have shade cloth suspended above them to help moderate temperatures. In a cold frame, plants grow best at 18–29 °C. If air temperature exceeds 29 °C, the top must be opened to allow ventilation.

Hoop houses and polyethylene (“poly”) tunnels are versatile, inexpensive options. They are usually constructed of semicircular frames of polyvinyl chloride (PVC) or metal pipe covered with a single layer of heavy polyethylene and are typically quite long. The cover on hoop houses is changed or removed during the growing season to provide a different growing environment, eliminating the need to move the crop from one structure to another.

Shadehouses are the most permanent of semicontrolled propagation environments. In the tropics, shadehouses are commonly used to propagate plants under conditions of intense sunlight (Fig. 2a). When used for growing, shade houses can be equipped with sprinkler irrigation and fertilizer injectors. When the shade is installed on the sides of the structure, shadehouses are very effective at protecting crops from wind and therefore help to reduce transpiration. Shadehouses can also be built with local materials (Fig. 2b).

## Fully Controlled Environments

Fully controlled environments control most or all of the limiting environmental factors. These propagation environments have the advantage that most crops can be grown faster with more uniform quality than those grown in propagation environments with less control. Examples include growth chambers (high-cost option used almost exclusively for research) and greenhouses. Tropical nurseries with large forestry and restoration programs often make use of greenhouses. These benefits must be weighed against the higher costs of construction and operation. The more complicated a structure is, the more problems that can develop. All greenhouses are transparent structures that allow natural sunlight to be converted into heat. At the same time, greenhouses are poorly insulated and require specialized cooling and ventilation systems to regulate temperatures. Jacobs et al. (2014) describe engineering considerations necessary when designing greenhouses for tropical plant production.

**Fig. 2** Shadehouses protect plants from intense sunlight, rain, or wind and can be constructed of wood frames with lath or metal frames with shadecloth (**a**) or created with locally available materials (**b**) (Photos by Tara Luna)

One specialized, fully controlled environment is for rooting cuttings, the most common type of vegetative propagation. These “rooting chambers” create specific conditions to stimulate root initiation and development. Because cuttings do not have a root system, rooting chambers must provide frequent misting to maintain high humidity to minimize transpiration. Root formation is stimulated by warm temperatures and moderate light levels; these conditions maintain a high level of photosynthesis. Therefore, many rooting chambers are enclosed with polyethylene coverings that, in addition to maintaining high humidity, keep the area warm. If the chambers are outside, the covering further protects cuttings from rain and drying winds.

## Modifying Light and Temperature

To reduce light intensity and the resultant heat, growers apply shadecloths to propagation environments. Shadecloths are rated by the amount of shade they produce, ranging from 30 % to 80 %. Black has been the traditional color because it is relatively inexpensive, but now shadecloth comes in white, green, and reflective metal. Because black absorbs sunlight and converts it into heat that can be

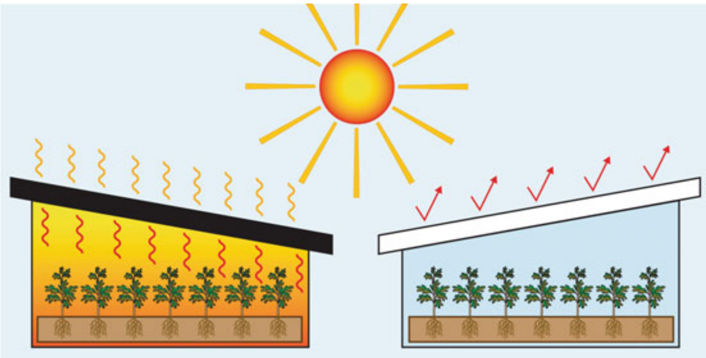

**Fig. 3** Compared with white or reflective shadecloth, black shadecloth can absorb heat and radiate it into the propagation environment (Illustration by Jim Marin)

conducted into the propagation structure (Fig. 3), black shadecloth should never be installed directly on the covering of any propagation structure, but instead needs to be suspended above it to facilitate air movement. Although more expensive than black shadecloth, white or aluminized shade fabrics are better for tropical environments and will do a much better job of cooling the propagation environment while still keeping light levels high. Applying a series of shadecloths, each with a lesser amount of shade, during a period of time is a good way to gradually harden nursery stock and prepare it for outside conditions. Thermometers that record the maximum and minimum temperatures during the day are simple and economical instruments that can help growers monitor subtle microclimates within any propagation environment.

## Growing Media

A growing medium can be defined as a substance through which plant roots grow and extract water and nutrients. Selecting a good growing medium is fundamental to good nursery management and is the foundation of a healthy root system. Growing media for use in container nurseries is available in two basic forms: organic-based (sometimes called “soil-free”) and soil-based. Compared with soil-based media, organic-based media (a base of organic materials that may be compost, peat, coconut coir, or other organic materials, mixed with inorganic ingredients) promotes better root development.

### Physical Properties of Growing Media

Physical characteristics of a growing medium determine how well it holds water and allow gas exchange with roots. Four characteristics – water-holding capacity, aeration, porosity, and bulk density – are inter-related and greatly influence plant development. In general, nursery managers want a medium with high porosity (micropores and macropores). Micropores increase water-holding capacity because they hold water against the pull of gravity until plants use it. Macropores are filled with air after excess water has drained away because of gravity and contribute to aeration of the medium by providing pathways for oxygen to reach roots and carbon dioxide generated by root respiration to dissipate. The ratio of micropores and macropores varies by the types and sizes of the growing medium ingredients (discussed below). Thus, for water-loving plants, a desired medium has more micropores to increase water-holding capacity, but a drought-tolerant plant, or cuttings, would be grown in a medium with more macropores to prevent water-logging and rotting. Soils with more micropores usually have a higher bulk density (the weight per volume of the medium) whereas well-drained media, especially those with pumice or perlite, have lower bulk densities. A medium with low bulk density can be compressed into a container so that the macropores are destroyed, thus resulting in a higher bulk density with subsequently more micropores and a greater water-holding capacity. An ideal growing medium is lightweight enough to facilitate handling and shipping while still having enough weight (a sufficient bulk density) to provide physical support to the plant.

## Chemical Properties of Growing Media

The most important chemical properties of a growing medium are fertility, pH, and cation exchange capacity (CEC). Plants rely on the growing medium to meet their increasing demand for mineral nutrients for growth. Many nursery managers prefer media with inherently low fertility to discourage damping-off during the establishment phase and add soluble fertilizers to media throughout the remainder of the growing season, whereas others blend controlled-release fertilizer into the medium or top dress the medium during the growing season. If fertilizers are difficult to obtain or cost prohibitive, organic amendments such as manure or compost can be included in the growing medium. The availability of those nutrients depends on the pH of the growing medium (Fig. 4) and most plants tend to grow best at pH levels between 5.5 and 6.5. Exceptionally high or low pH levels also affect the abundance of pathogens and beneficial microorganisms. CEC refers to the ability of a growing medium to chemically hold positively charged ions. The CEC of a growing medium reflects its nutrient storage capacity, thus it provides an indication of how often fertilization will be required. Because nutrient leaching occurs during irrigation, container nurseries prefer a growing medium with a very high CEC.

## Biological Properties of Growing Media

Growing media ingredients may contain pathogenic bacteria or fungi; those that do should be sterilized or pasteurized before use (see below). Organic-based growing media are preferred in nurseries because they are generally pest free. Although peat

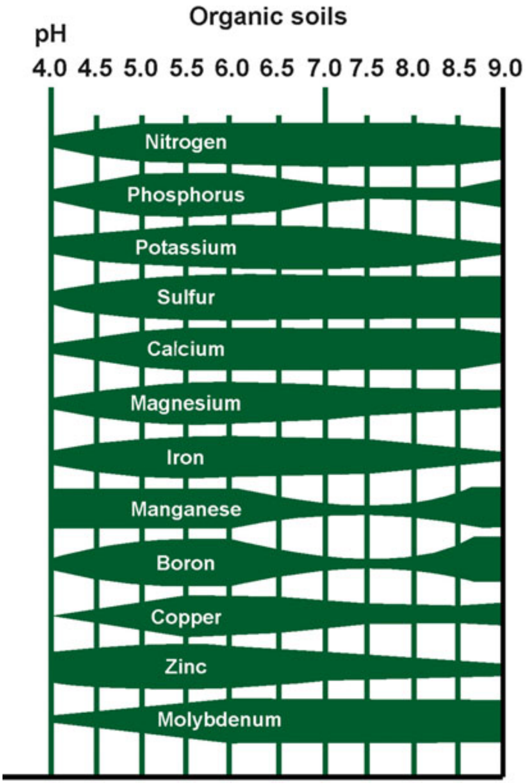

**Fig. 4** The pH of the growing medium affects availability of all mineral nutrients. In organic-based growing media, maximum availability occurs between 5.5 and 5.6 (Illustration modified from Bunt (1988))

moss is not technically sterile, it rarely contains pathogens or weed seeds when obtained from reliable sources. Vermiculite and perlite are rendered completely sterile by hot temperatures (≤1,000 °C) during manufacturing. Well-prepared composts are generally pest free because sustained, elevated temperatures during composting kill most pathogens.

## Growing Media Ingredients

Once the functions and characteristics of growing media are understood, an effective and affordable growing media can be developed. A typical growing medium is a composite of two or three ingredients selected to provide certain physical, chemical, and/or biological properties. Mixtures of organic and inorganic ingredients are popular because these materials have opposite, yet complementary, properties (Table 1). Here are some of the common components of growing media:

- **Peat Moss** – The horticultural and uniform properties of *Sphagnum* peat moss make it the only peat moss used in plant nurseries. Most peat moss comes from Canada, some comes from New Zealand, and the one known tropical source is

**Table 1** Different chemical and physical properties of some common materials used to create growing media (Buamscha and Altland 2005; Johnson 1968; Lovelace and Kuczmarski 1994; Newman 2007)

| Component | Bulk density | Porosity: water | Porosity: air | pH | Cation exchange capacity |
|---|---|---|---|---|---|
| Organic ingredients | | | | | |
| *Sphagnum* peat moss | Very low | Very high | High | 3–4 | Very high |
| Bark | Low | Low | Very high | 3–6 | High |
| Coir | Low | High | High | 6–7 | Low |
| Sawdust | Low | High | Moderate | 3–6 | Low |
| Rice hulls | Low | Low | Moderate | 5–6 | Low |
| Compost | Variable | Variable | Variable | 6–8 | High |
| Inorganic ingredients | | | | | |
| Vermiculite | Very low | Very high | High | 6–8 | High |
| Perlite | Very low | High | High | 6–8 | Very low |
| Sand | Very high | Moderate | Very low | Variable | Low |
| Pumice | Low | Low | High | 6–8 | Low |

Indonesia (Miller and Jones 1995). Therefore, it is expensive and problematic to import peat for most tropical nurseries. Some nurseries may use peat as a transition component, comparing peat's properties to local materials, such as composts or coir, to develop local alternatives for growing media while moving forward with plant production.

- **Compost** – Composts are an excellent sustainable organic component for any growing medium and significantly enhance the medium's physical and chemical characteristics by improving water retention, aeration porosity, and fertility (Fig. 5a). Some compost has also been found to suppress seed- and soil-borne pathogens. Compost quality can vary considerably among source materials and even from batch to batch; each material and batch should be tested before general use. Nursery managers should be able to find a sustainable source of organic matter that can be composted and used as a growing media component. Mature compost should not produce an unpleasant odor or heat before incorporating into a growing medium. Landis et al. (2014a) provide a detailed description on producing compost for tropical nursery use.
- **Coconut Coir** – A byproduct of processing coconut husks, coir, sometimes called coir dust or coco peat, has proven to be an excellent organic component (Noguera et al. 2000) and is readily available in some tropical locales (Fig. 5b). Physical and chemical properties of coir can vary widely from source to source (Evans et al. 1996).
- **Sawdust** – Raw sawdust can negatively affect nutrient availability, especially nitrogen, but its properties can be improved with composting (Fig. 5c; Miller and Jones 1995). However, the inherent differences in chemical properties among tree species make the suitability of sawdust extremely variable.

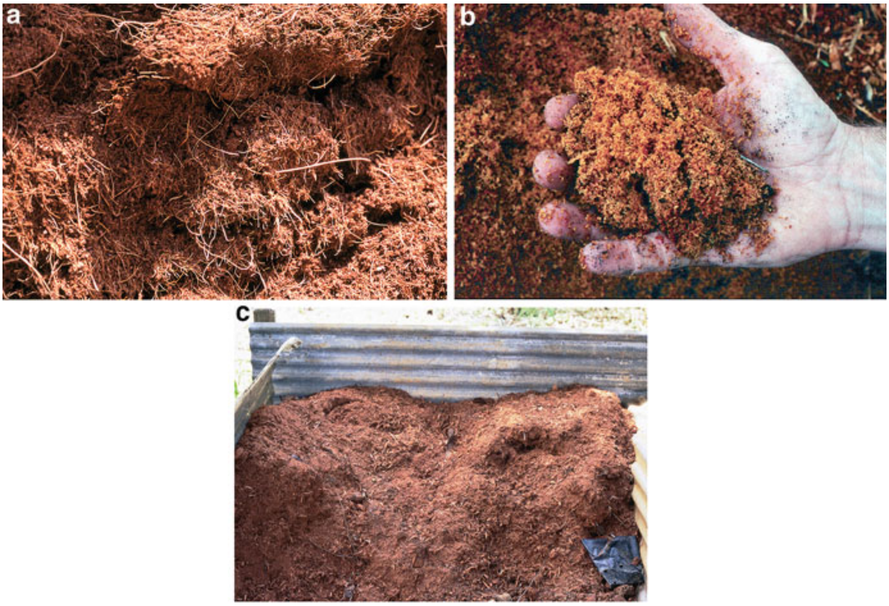

**Fig. 5** Common organic ingredients of growing media include coconut coir (**a**), sawdust (**b**), or composted tree bark (**c**) (Photos (**a**) and (**c**) by Tara Luna, photo (**b**) Thomas D. Landis)

- **Rice Hulls** – Rice hulls or husks have been used as a component for many years in Indonesia (Miller and Jones 1995). Several nurseries have used composted, screened, and hammer-milled rice hulls in place of composted bark (Landis and Morgan 2009).
- **Vermiculite** – Vermiculite is a popular component because it has many desired qualities, such as a very low bulk density, an extremely high water-holding capacity, a neutral pH, a high CEC, and small amounts of potassium and magnesium. Vermiculite is sold based on its particle size, which determines the relative proportion of aeration and water-holding porosity.
- **Perlite** – Perlite particles have a unique closed-cell structure so that water adheres only to their surface; they do not absorb water as peat moss, coir, or vermiculite do. Therefore, growing media containing perlite are well drained and lightweight. Perlite is also rigid and does not compress easily, which promotes good porosity. One safety concern is that perlite can contain considerable amounts of very fine particle sizes that cause eye and lung irritation during mixing. Wetting the material while mixing and wearing dust masks and goggles can reduce this risk.
- **Pumice and Cinder** – The porous nature of pumice particles improves aeration porosity but also retains water within the pores. Pumice is the most durable of the inorganic ingredients and so resists compaction. Cinder is another type of volcanic rock and a common component in volcanic areas.

- **Sand** – The composition of sand varies widely. When considering if local sand is a suitable component, the type of sand and its particle sizes must be determined. For example, some silty river sands with small particle size can negatively affect growing media by making them excessively heavy and not contributing to improved aeration.
- **Field Soil** – Field soil is not recommended for growing nursery plants. If circumstances require a nursery to include some field soil in their media while more affordable and sustainable alternatives are being developed, dark topsoil should be selected. Soil-based mixes are safest for transplant media when transplanting into larger containers, such as polybags or larger containers (>3.5 L). The properties of soil-based mixes make them unsuitable for smaller containers, and the risk of disease makes them unsuitable in media for germinating seeds or rooting cuttings. Soil should comprise no more than 10–20 % of the transplant media by volume although some nurseries use up to 30 %.

## Developing and Mixing Growing Media

Every nursery manager needs to be able to experiment and find suitable, local, affordable ingredients to create good growing media. Three general types of growing media are used in container nurseries:

1. **Seed Propagation**. For germinating seeds or establishing germinants (sprouting seeds), the medium must be sterile and have a finer texture to maintain high moisture around the germinating seeds.
2. **Rooting Cuttings**. Cuttings are rooted with frequent misting, so the growing medium must be very porous to prevent waterlogging and allow good aeration necessary for root formation.
3. **Transplanting**. When smaller seedlings or rooted cuttings are transplanted into larger containers, the growing medium is typically coarser.

Because of the diverse characteristics of various growing media ingredients, a growing medium can be formulated with nearly any desired property. The physical, chemical, and biological properties of each growing medium strongly interact with nursery cultural practices, particularly irrigation, fertilization, and container type. When considering a new growing medium, first test it on a small scale with several different species and evaluate its suitability before making a major change to the whole crop.

A variety of commercial mixes that feature combinations of organic and inorganic ingredients are available. Many brands also contain a wide variety of amendments including fertilizers, wetting agents, hydrophilic gels, and even beneficial microorganisms. Many media are formulated for crops other than tropical plants and may do more harm than good; always check the label to be sure of exactly what is in the mix. Many nursery managers prefer to mix their own custom growing media. In addition to saving money, custom mixing is particularly useful in small nurseries where separate mixes are needed to meet propagation requirements of different species.

Some media may also include amendments – supplemental materials that contribute less than 10 % of the mixture including fertilizers, lime, surfactants, hydrogels, and mycorrhizal inoculum. Some of these materials may be undesirable because they are formulated for other crops and are detrimental to native plant growth. If amendments are added to the growing medium, it is important that they be added uniformly and tested on a small scale before widespread usage.

Whitcomb (2003) emphasized that improper media mixing is one of the major causes of variation in container plant quality. Small batches of growing media ingredients can be mixed by hand and larger batches can be mixed on any clean, hard surface using shovels. Some organic ingredients repel water when dry, so frequently misting the media with water at regular intervals during mixing improves water absorption. Do not compress or compact during mixing. Nursery managers that regularly require larger quantities of custom growing media should consider purchasing a mixer. A cement mixer works well as long as care is taken to avoid excessive mixing, which breaks down the size and texture of ingredients. When handling growing media, workers need to follow safety precautions to protect from dust and infections. Perlite dust is of particular concern because of potential for silicosis, an inflammation that occurs over time when dust that contains silica is inhaled into the lungs and open wounds should be covered to prevent infections.

## Treating Growing Media Ingredients

Some growing media ingredients may need to be leached, pasteurized, and /or screened before use to reduce potential damage to plants. Using fresh water to leach out salts may be necessary for materials such as coir, sand, sawdust from mills near the ocean, and composts with excessive soluble salt levels (Carrion et al. 2006; Landis and Morgan 2009). Pasteurization, especially of organic ingredients, can prevent the introduction of pests, weeds, and diseases into the nursery (Fig. 6). Most inorganic components are inherently sterile. Heat generated during the composting process will kill pathogens and other pests, but field soil should be pasteurized. Heat pasteurization is the most common way of treating growing media and includes moist heat from steam, aerated steam, or boiling water or dry heat from flame or electric pasteurizers or microwave ovens. Small pasteurizing equipment is available for nurseries and some nurseries have developed their own pasteurization process using fire or solar heat. Some ingredients, such as soil, sand, and cinder, may require screening or sifting to achieve the desired particle size. It may be necessary to sift twice, once with a small mesh to eliminate material larger than desired, and a second time with a larger mesh to remove material smaller than desired.

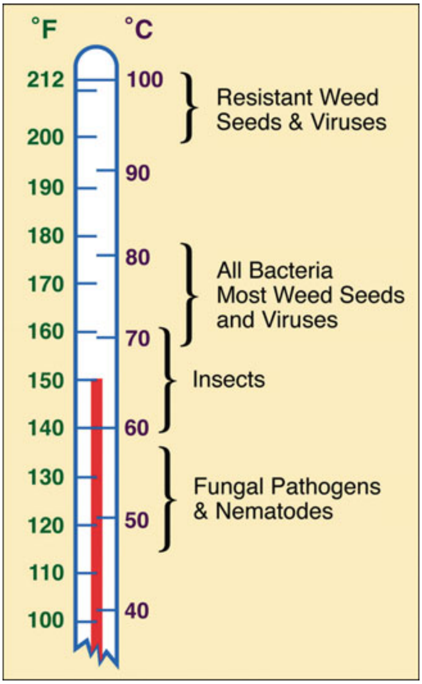

**Fig. 6** Necessary temperatures for heat pasteurization vary depending on the target pest. Effective control is achieved if the target temperature is held for 30 min (Illustration from Landis et al. (2014a) by Jim Marin)

## Testing Growing Media

To preclude surprises, nursery managers test compost and growing media well in advance of use and retain the results to compare with new or experimental batches (Grubinger 2007) and to develop and refine suitable alternative mix(es) with similar favorable properties. One easy and effective test is a plant bioassay (Grubinger 2007). Put a sample of the growing medium in the containers that will be used in the nursery, sow an abundantly available, fast-growing species into the medium, and observe how the planting performs during a few weeks. If the mix works, it is ready to try in the nursery.

The salinity (salt level) of the growing medium is a key parameter affecting the development and health of roots. Salts may come from growing media ingredients, irrigation water, and from added fertilizers. Routinely measuring electrical conductivity (EC) monitors the amount of nutrients and salts present to ensure they are in the appropriate ranges for the species grown (Table 2). Excessively high salt levels can damage or even kill succulent young plants. For more details on proper technique with EC meters, see Landis and Dumroese (2006).

For more formal testing, growing media samples can be sent to a soil-testing laboratory (private, local extension office, or university) for testing. A measurement of pH, soluble salts (electrical conductivity), and nutrients should be requested (Grubinger 2007). Results can vary among laboratories depending on their

**Table 2** Electrical conductivity (EC) guidelines for artificial growing media (Timmer and Parton 1982)

| EC range (μS/cm) | Salinity rating general guidelines |
|---|---|
| 0–12,000 | Low |
| 1,200–2,500 | Normal |
| 2,500–3,000 | High |
| 3,000–4,000 | Excessive |
| >4,000 | Lethal |

μS/cm = microSiemens per centimeter

**Fig. 7** Nurseries use a variety of containers to produce different species and stocktypes (Photo by Diane L. Haase)

procedures, so it is best to select one laboratory and use them for testing year to year, provided that the data appear accurate and consistent.

## Containers

A suitable container could be anything that holds growing media, drains, allows for healthy root development, does not disintegrate before outplanting, and allows for an intact, healthy root system to be removed with a minimum of disturbance to the plant. Most nurseries grow a wide variety of species and therefore several different containers are required (Fig. 7). In general, the following points hold true regarding container type: Plants that develop shallow, fibrous root systems, as most forbs do, grow better in shorter containers. Plants with long taproots, such as many kinds of trees, grow better in taller containers. And, plants with multiple, thick, fleshy roots, and species with thick, fleshy rhizomes grow better in wide containers.

Many types of containers are available and each has its advantages and disadvantages concerning plant development, economics, and efficiency under operational conditions (Landis et al. 2014b). It is a good idea to try new containers for each species on a small scale before buying large quantities. Several containers types are used in container plant nurseries and can vary considerably in attributes and size.

## Container Characteristics Affecting Plant Development

- **Volume** – Container volume dictates how large a plant can be grown in it and this varies by species, target plant size, growing density, length of the growing season, and growing medium used. Larger containers occupy more growing space and take longer to produce a firm root plug so therefore are more expensive to produce, store, ship, and outplant but the benefits, however, may outweigh the costs if the outplanting objectives are more successfully satisfied.
- **Height** – Container height determines the depth of the root plug, which may be a consideration on dry outplanting sites (where a deep root system that can stay in contact with soil moisture is desired) or sites with shallow soils (where only a short root system can be planted).
- **Diameter** – Broad-leaved trees, shrubs, and herbaceous plants generally need a larger container diameter so that irrigation water applied from above can penetrate the dense foliage and reach the medium. The container diameter must also be large enough to accept the seeds.
- **Shape** – Containers are available in a variety of shapes and most are tapered from top to bottom. Most containers are round but some are square and maximize the growing space used in the nursery. Container shape is important as it relates to the type of outplanting tools used and the type of root system of the species grown.
- **Density** – The distance between plants is important because it affects the amount of light, water, and nutrients that are available to individual plants (Fig. 8a). In general, plants grown at closer spacing grow taller and have less stem diameter than those grown farther apart (Fig. 8b). Plant leaf size greatly affects growing density. Broad-leaved species grow better at fairly low densities, whereas smaller leaved and needle-leaved species can be grown at higher densities. Trays holding individual containers provide some flexibility in density because, as the plants grow, containers can be rearranged to allow greater space among plants (Fig. 8c).
- **Root Control** – Some plants have aggressive roots that quickly reach the bottom of the container and may spiral or become rootbound. Many containers have vertical ribs to force the roots downward and prevent spiraling. Chemical pruning involves coating the interior container walls with chemicals that inhibit root growth. Several companies have developed containers that feature air slits on their sides to promote pruning and mitigate root deformation (Fig. 9).
- **Drainage** – Containers must have a bottom hole or holes large enough to promote good drainage and encourage "air pruning." The drainage hole must also be small enough to prevent excessive loss of growing medium during the container-filling process.
- **Color and Insulation** – Color and insulating properties of the container affect medium temperature, which directly affects root growth. Black containers can

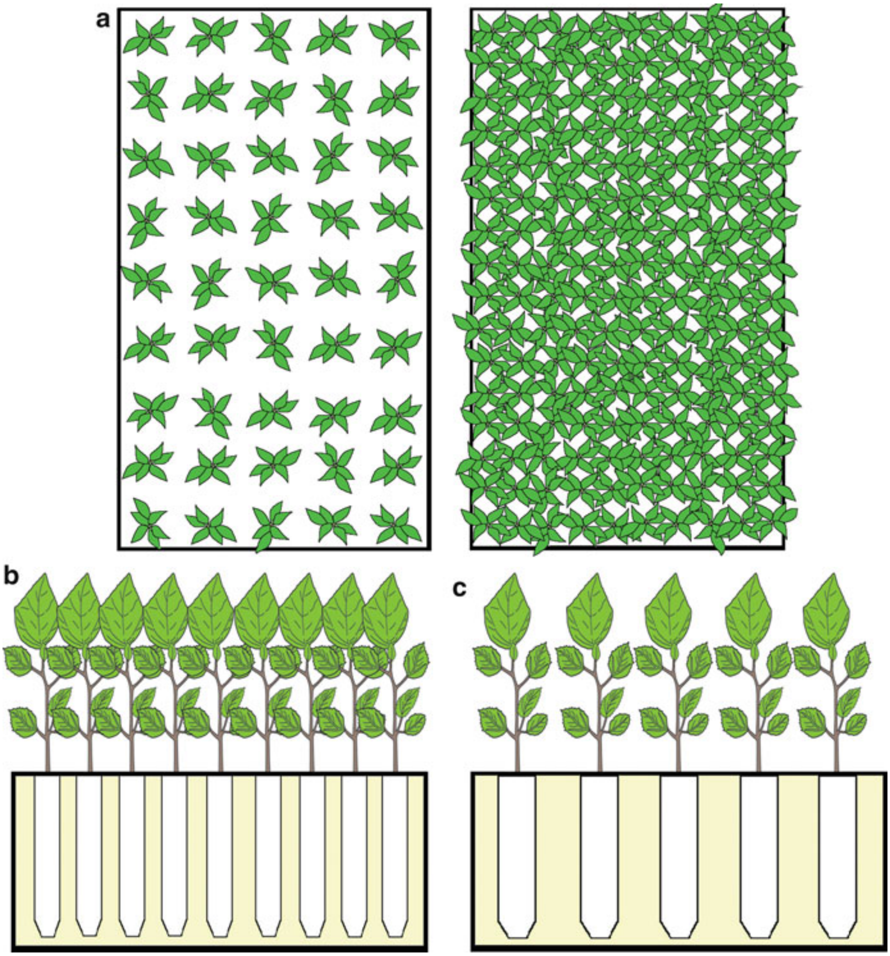

**Fig. 8** Next to volume, density (spacing) is the most important characteristic in container choice (**a**). Plants grown too close together become tall and spindly and have less stem diameter (**b**). Trays with removable containers are popular because they allow flexibility in spacing between plants (**c**) (Adapted from Dumroese et al. 2008)

quickly reach lethal temperatures in full sun whereas white ones are more reflective and less likely to have heat buildup.

## Economic and Operational Factors Affecting Container Choice

- **Cost and Availability** – In addition to the purchase prices, remember to consider associated expenses for various container types, such as shipping and storage costs. Nursery managers in the tropics often face high shipping costs and long

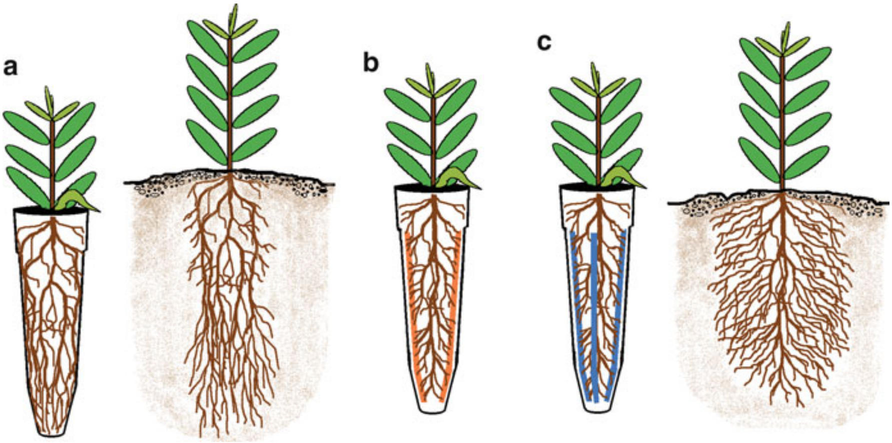

**Fig. 9** Plants with aggressive roots often exhibit spiraling and other deformities after outplanting. If rootbound, roots often do not grow out beyond the original plug (**a**). Containers coated with copper will chemically prune roots (**b**) and other containers are available with lateral slits to reduce spiraling and encourage air pruning on the side of the plug (**c**). (Illustrations adapted from Dumroese et al. 2008).

shipping times. Also consider the potential for long-term availability to ensure that ample supplies can be secured in the future.

- **Durability and Reusability** – Containers must maintain structural integrity and contain root growth during the nursery period. The intense heat and ultraviolet rays in container nurseries can cause some types of plastics to become brittle and break, although many container plastics now contain ultraviolet (UV) inhibitors. While some containers are designed to be used only once, others can be reused for 10 or more crop rotations. The purchase cost of reused containers can be amortized over their life span after adjusting for the cost of handling, cleaning, and sterilizing the containers between crops.
- **Return from Customers** – Reusing containers is important; it saves money and resources and protects the environment from waste. Charging a refundable container deposit (similar to bottle deposits for beverage containers) encourages clients to return containers to the nursery. All containers should be washed and sterilized before reuse in the nursery; even though disease symptoms may not be apparent, disease organisms accumulate in non-treated containers and reduce growth (Dumroese et al. 2002).
- **Ease of Handling** – Containers are typically moved several times during crop production, so handling is a major concern from logistic and safety standpoints. Collapsible or stackable containers may have lower shipping and storage costs but labor is required to prepare them for filling and sowing. Large containers are increasing in popularity, but they become heavy when saturated with water. Weight must be considered for shipping and field planting.

- **Ability to Cull, Consolidate, and Space** – One advantage of tray containers with interchangeable cells is that cells can be rearranged. During thinning, empty cells can be replaced with those containing plants. During roguing, diseased or undesirable plants can be replaced with healthy plants. For species that germinate during a long period, plants of the same size can be consolidated and grown under separate irrigation or fertilizer programs. Thus, consolidation can save a considerable amount of growing space. Another unique advantage is that cells can be spaced further apart by leaving empty slots; this practice is ideal for larger leaved plants and for promoting air circulation later in the season when foliar diseases can become a problem.

## Ways to Preclude Problems If Using Polybags and Polytubes

Bags made of black polyethylene (poly) plastic sheeting are the most commonly used nursery containers in the world because they are inexpensive and easy to ship and store (Fig. 10a). Polybags often produce seedlings with poorly formed root systems that spiral around the sides and bottoms of the smooth-walled containers. This problem worsens when seedlings are held over and not outplanted or transplanted at the proper time.

In cases in which converting to hard plastic containers would be operationally or financially impractical, ways exist to improve container production using polybags. Some of these cultural modifications include (Landis 1995):

- Managing container seedlings as a perishable commodity with a limited “shelf life.” This concept is particularly critical in tropical nurseries where seedlings grow year round. If seedlings cannot be outplanted when their roots fill the container, then they must be transplanted into a larger container. Holding over polybag seedlings is not an option.
- Using polytube containers (a polybag open at both ends, sometimes called a polysleeve) instead of polybags (Fig. 10b). These containers can usually be obtained from the same supplier as polybags or cut from a continuous roll with no bottom (Jaenicke 1999). Poly tubes eliminate much of the root spiraling. Poly tubes will hold growing media if they are properly filled and placed on elevated screen-bottomed trays to promote air pruning of roots (Fig. 10c).
- Using copper-coated polytubes or polybags. Plants grown in copper polybags produce a much finer, fibrous, non-circling root system that is well distributed throughout the containers.
- Switching from soil-based to “artificial” or organic-based growing media (based on composts, bark, or other materials instead of soil).
- Carefully transplanting germinants or direct-seeding into the polytube containers to avoid root deformations.

**Fig. 10** Polybags are inexpensive containers that can produce good plants (**a**) but root spiraling is often serious. Open-bottomed polytubes (**b**) in trays (**c**) can help solve that problem (Photos by Tara Luna)

## Water Quality and Irrigation

Water is the single most important biological factor affecting plant growth and health. Determining how, when, and how much to irrigate is a crucial part of nursery planning and day-to-day operations. Adequate watering is particularly important with container plants because they can dry out quickly, but excessive watering can lead to root disease and contribute to other problems with seedling growth.

Tropical nurseries typically grow a wide range of species with different water requirements, and these water requirements change as the plant moves through the three phases of growth (establishment, rapid growth, and hardening; described below). The nursery might have various propagation areas and corresponding irrigation zones that provide for the changing needs of plants during these phases. The best design for any irrigation system comes from understanding the needs of the plants, the factors that affect water availability, and the details of how, when, and why to water.

Tropical plant nurseries can use water from several different sources, including rivers, ponds or reservoirs, rainwater, groundwater, and municipal sources. New nurseries need to evaluate the quantity, quality, and seasonal availability of all potential water sources. For surface or groundwater, a hydrologic survey and analysis of local water rights needs to be conducted before nursery development. Surface water sources that have flowed through agricultural land need to be tested for waterborne pests or herbicides and may need to be treated. Rainwater is an attractive source of high-quality water for tropical nurseries if enough can be collected from the roofs of buildings and stored in tanks until needed.

## Water Quality and Quantity

The amount of water to grow a crop varies tremendously between humid and arid locations. Remember that a nursery also needs water for operational requirements other than irrigating crop and that a nursery that starts small may choose to expand. Therefore, ensure an abundance of water is available to meet present and future needs. Even in cases with access to a steady, reliable, high-quality water source, an emergency backup system is always a good idea. A prudent investment is a backup water storage tank containing sufficient water to meet the nursery’s needs for at least 1 week.

Water quality needs to be a primary consideration during nursery site evaluation. For irrigation purposes, water quality is determined by the quantities of salts and pests in it. A salt is defined as any chemical compound that releases charged particles (ions) when dissolved in water. Some salts are fertilizers while other salts can reduce growth or even cause injury or death. Excessive dissolved salts in irrigation water can clog nozzles and accumulate in growing media and eventually harm plant tissue. The most characteristic symptom of high salinity is reduced growth and burn or scorch of leaf margins or tips (Fig. 11). Excessive dissolved salts result from local climatic or geologic influences, saltwater intrusion, high fertilization rates, or poor irrigation practices. Test results for salinity are traditionally expressed as electrical conductivity (EC); the higher the salt concentration, the higher the EC (Table 3). The EC can be checked at the nursery using a conductivity meter, or by sending water samples to a local laboratory.

Tropical nurseries that use irrigation water from surface water sources such as ponds, lakes, or rivers may encounter problems with pests: weeds, pathogenic fungi, moss, algae, or liverworts. Recycled nursery irrigation water should also be

**Fig. 11** Agricultural water quality is determined by the level of soluble salts because they can accumulate and eventually "burn" seedling foliage (Photo by Thomas D. Landis)

**Table 3** Water-quality standards for nursery irrigation water (Modified from Landis et al. 1989a; Robbins 2011)

| Quality index | Optimal | Unacceptable |
|---|---|---|
| pH | 5.5–6.5 | |
| Salinity (μS/cm) | 0–500 | >1,500 |
| Sodium (ppm) | <50 | >50 |
| Chloride (ppm) | <70 | >70 |
| Boron (ppm) | <0.75 | >0.75 |
| Fluoride (ppm) | <1.00 | >1.00[a] |
| Iron (ppm) | <1.00 | >1.00 |

[a] Sensitive species may be damaged at lower levels

analyzed. Many weed seeds and moss and algal spores are small enough to pass through the irrigation system and can cause problems. Chlorination and some specialized filtration systems may remove many disease and pest organisms from irrigation water. Irrigation water, especially in agricultural areas, may be contaminated with residual pesticides, and these sources need to be tested for pesticide contamination during the nursery site selection process.

## Water Testing and Treatments

Water should be tested during the site selection process, once the nursery is established, and again at yearly intervals. A complete analysis of irrigation water consists of a salinity evaluation listing the concentrations of sodium, chloride, and boron, which are reported in parts per million (ppm) and the three standard water-quality indices: EC, toxic ion concentrations, and pH (Table 3). It should also be tested for the presence of pathogenic fungi during the site selection process and later if a problem is observed. Collect an irrigation water sample in a clean plastic bottle with a firm, watertight lid. Let the water run for several minutes and then rinse the sample bottle well before collecting the sample.

Establishing the nursery on a site with tested, good-quality water is the best way to preclude water-related problems. If existing water quality is poor, methods such as deionization and reverse osmosis can treat and improve irrigation water, but they are often prohibitively expensive and not feasible for most nurseries. To correct or safeguard against minor problems with otherwise good-quality water, however, chlorination and filtration are low cost and highly effective for container nurseries. Chlorination can kill fungi, bacteria, algae, or liverworts introduced through the irrigation system. A simple method is to mix household bleach (5.25 % sodium hypochlorite) at a rate of 18 ml per 1,000 L. This low dose (about 1 ppm) is not phytotoxic to a wide range of plant species (Cayanan et al. 2008) – but always test it first on a small subset before treating the entire crop. Filtration removes suspended or colloidal particles, thus preventing problems such as plugging or damaging irrigation equipment, as well as removing unwanted pests such as weed seeds or algae spores. Granular medium filters can remove fine sand or organic matter and are constructed so that they can be backflushed for cleaning. Surface filters include screens or cartridges of various mesh sizes to remove suspended material; screens must be physically removed and cleaned whereas cartridge filters are not reusable and must be regularly replaced. Handreck and Black (1984) recommend using filters small enough to remove particles greater than 5 μm in diameter, which will take care of most suspended materials.

## Determining When and How Much to Irrigate

When irrigating container crops, it is important to apply enough water such that some drips out the bottom of the container, but not so much that water streams out the bottom. The general rule is to apply approximately 10 % more water than is needed to completely saturate the entire growing medium profile during irrigation.

It is absolutely necessary to regularly monitor the moisture status of growing media. In small containers, the limited volume of moisture reserves means that critical moisture stresses can develop quickly. Visual and tactile assessments are the most common method of monitoring irrigation effectiveness. Monitoring can also include formal or informal assessments of container weight. In addition, various tools, such as tensiometers, electrometric instruments, balances, commercial moisture meters, or pressure chambers can be used to monitor irrigation efficacy (Landis et al. 1989a). Any equipment-based method must also be supported by actual observation (visual and tactile) and the grower's experience. A quantifiable technique, such as container weight (the difference between the container weight at field capacity and some target weight, for example 75 % of field capacity), ensures that proper irrigation frequency can be repeated by all staff for a particular crop for consecutive growing seasons (see Dumroese et al. 2012).

The amount of irrigation to apply varies during the growing season because of the three stages of plant development: establishment, rapid growth, and hardening (described in the chapter, "▶ Planning and Managing a Tropical Nursery").

The **establishment phase** is the time from when sown containers are placed in the growing area until true leaves form or cuttings begin to root. The growing medium needs to be brought to field capacity (some water dripping from the bottom). Thereafter, watering needs during establishment should be monitored carefully and tailored to the needs of the species. On the one hand, inadequate irrigations will allow seeds to dry out, decreasing germination success or causing total crop loss. On the other hand, excessive irrigation may create excessively wet conditions that promote damping-off and delay germination. Until the seeds germinate and begin to grow, water must be applied with the goal of replenishing the moisture in the thin surface layer of the medium. This practice is usually best accomplished by periodic misting or light irrigation with a very fine spray nozzle, which also protects germinating seeds from being moved or damaged by the force of the water. These fine sprays can also be used to control the temperature around germinating seeds; misting just enough to dissipate heat around the seedling.

During the **rapid-growth phase,** the plant experiences a large increase in shoot size, which increases the amount of water lost through transpiration so irrigations must be longer and more frequent. Water use can double or even triple during the rapid growth phase. No plants should ever be allowed to dry out completely. Nursery managers need to be aware of the varying water requirements for different species and adjust irrigation practices accordingly. The rapid growth phase is also the time when liquid fertilizers are most concentrated and water loss through transpiration is high, so growers must monitor for salt accumulation.

Once plants near the target size, the **hardening phase** begins. Manipulating irrigation frequency is an effective way to initiate the hardening of plants before shipment and outplanting. Because seedling growth is tied to moisture stress levels, growers can slow shoot growth and increase general resistance to stress by inducing mild water stress. This "drought stressing" procedure consists of withholding irrigation for short periods of time until the plants can be seen to wilt slightly or until some predetermined moisture stress is reached. For some species, this process may be repeated several times. After this stress treatment, the crop is returned to a maintenance irrigation schedule.

## Types of Irrigation Systems

The best method of applying irrigation water depends on the water requirements of the species being grown and on the size and complexity of the nursery (Table 4). In general, four methods (hand watering, microirrigation, overhead irrigation, and subirrigation) are the most commonly used, and individual nurseries may use one or more of them depending on the particular crops.

**Hand watering** is often the most practical irrigation strategy for small nurseries, nurseries producing a wide diversity of species with radically different water requirements, or nurseries in the startup phase. Although the task may appear easy, it is challenging to uniformly apply the proper amount of water to diverse species of plants in a diverse suite of containers at different growth stages. Nursery

**Table 4** Advantages and Disadvantages for four types of irrigation systems for container nurseries (Landis and Wilkinson 2014)

| Advantages | Disadvantages |
|---|---|
| **Hand watering** | |
| • Requires inexpensive equipment that is simple to install<br>• Is flexible and can adjust for different species and container sizes<br>• Irrigators have a daily connection to the crop and can scout out diseases or other potential problems<br>• Allows water to be directed under plant foliage, reducing risk of diseases | • Is time consuming and labor intensive<br>• Involves a daily responsibility including weekends and holidays<br>• Requires skill, experience, and presence of mind to do properly<br>• Presents a risk of washing out or compacting growing medium |
| **Microirrigation** | |
| • Water is delivered directly to the root zone of plants (not to foliage, where it may cause disease)<br>• Use of water is very efficient; less than 10 % of applied water is wasted<br>• Delivery is uniform; an even amount of water is applied to each container<br>• Infiltration rate is good (because of slow delivery)<br>• The amount of leachate is low | • Designing the system and installing individual emitters for each plant is difficult and time consuming<br>• It is not generally efficient to install for plants grown in containers smaller than 4 L in size<br>• Each irrigation station must run a long time because of slow water delivery<br>• Emitters can plug easily (water filtration and frequent irrigation system maintenance is required)<br>• With drippers, it is difficult to verify water delivery visually; often, problems are not detected until it is too late |
| **Sprinkler irrigation** | |
| • Relatively simple and inexpensive to design and install<br>• A variety of nozzle patterns and application rates are available<br>• Water distribution patterns can be measured with a cup test | • Foliar interception makes overhead watering ineffective for large-leaved crops<br>• Irrigation water can be wasted because of inefficient circular patterns<br>• An increased risk of foliar diseases is possible from excessive water on leaves<br>• For overhead sprinklers, nozzle drip from residual water in lines can harm germinants and young plants<br>• For basal sprinklers, irrigation lines must run along the floor, creating obstacles for workers and equipment |
| **Subirrigation** | |
| • Although commercial products are available, subirrigation systems can be constructed from affordable, local materials<br>• Foliage remains dry, reducing the risk of foliar diseases<br>• Water use is efficient (up to 80 % less water use than overhead watering systems)<br>• Application among plants is very uniform<br>• Lower fertilizer rates are possible<br>• Reduced leaching of mineral nutrients is possible<br>• Drainage water can be captured for reuse or recycling<br>• No splashing disrupts or displaces mulch, germinants, or medium<br>• Provides the ability to irrigate different size containers and different age plants concurrently<br>• Is efficient in terms of time and labor requirements following installation | • Overhead or hand watering may be required to ensure sufficient surface moisture until seeds germinate<br>• No leaching occurs, so it cannot be used with poor-quality water because salt buildup would occur<br>• Less air pruning of roots occurs<br>• Risk of spreading waterborne diseases is greater<br>• High humidity within plant canopy is possible |

managers need to ensure that irrigators have a conscientious attitude and are properly trained to work effectively with water application.

For nurseries that grow plants in containers 4+ L in size, **microirrigation** can be an efficient watering method. Microirrigation usually involves polyethylene pipe fitted with microsprayers (sometimes called “spitters” or “spray stakes”), drippers inserted individually into each container, or smaller lateral tubing to reach all areas on the bench. This system makes very efficient use of water because it is applied directly to medium in each container.

Many types of **overhead irrigation** systems exist, ranging from fixed sprinklers to moving boom systems. Fixed overhead sprinkler systems consist of a series of parallel irrigation lines, usually constructed of plastic polyvinyl chloride pipe, with sprinklers spaced at uniform intervals to form a regular grid pattern. The most expensive but efficient type of overhead sprinkler irrigation is the moveable boom, which applies water in a linear pattern. Moveable booms are generally considered too expensive for smaller nurseries but should be considered for large operations. For more information, see Landis et al. (1989a). A full discussion of types of irrigation designs and calculations is available in Stetson and Mecham (2011).

Wide leaves combined with the close spacing of plants in a nursery create a canopy that intercepts most of the water applied through overhead irrigation systems, reducing water use efficiency and creating variable water distribution among plants. These problems can be precluded by **subirrigation** systems, which offer a promising alternative for tropical plant nurseries. Subirrigation has been successfully used to grow many native plants (Pinto et al. 2008; Dumroese et al. 2006; Davis et al. 2008). In subirrigation systems, the bottoms of containers are temporarily immersed in water on a periodic basis (for example, for a few minutes). The water is then drained, leaving the growing medium thoroughly wet while the leaves remain dry. The discarded water can be retained and reused; a worthy feature when the supply of good-quality irrigation water is restricted.

## Plant Nutrition and Fertilization

Plants require adequate quantities of mineral nutrients in the proper balance for basic physiological processes and to promote rapid growth and development. Young plants rapidly deplete mineral nutrients stored within their seeds, and cuttings have limited nutrient reserves. Therefore, nursery plants must rely on root uptake of nutrients from the growing medium.

An important nutrition concept in plant nutrition is Liebig’s Law of the Minimum, which, when applied to plants, states that growth is limited by the mineral nutrient in shortest supply. Just as important as the absolute quantities of nutrients available to plants is the balance of nutrients. The proper nutrient balance is relatively consistent among plant species. Healthy plant tissue contains approximately 100 parts of nitrogen to 50 parts of phosphorus, to 15 parts of potassium, to 5 parts of magnesium, or to 5 parts of sulfur. On a practical basis, most nurseries use complete fertilizers that contain a balance of all mineral nutrients.

## Sources of Mineral Nutrients

Plants produced in tropical nurseries may acquire nutrients from several different sources, including the growing medium, irrigation water, beneficial microorganisms, and fertilizers. Many tropical nurseries use organic-based (soil-less) growing media that are essentially infertile, which enables nursery managers to apply the correct type of fertilizer, in the correct amount, and at the correct time. Native soils and composts contain higher nutrient concentrations than commercial growing media but rarely enough for the fast growth rate and nutrient balance desired in nurseries.

To achieve the desired plant growth and health, fertilizers are the most common source of mineral nutrients. Many different types of fertilizers are used and vary according to their source materials, nutrient quantities, and mechanisms of nutrient delivery.

Fertilizers can be broadly organized into two types: **organic** and **synthetic** (Landis and Dumroese 2011). Because of the variability involved, it is difficult to compare organic and synthetic fertilizers but some generalizations can be made (Table 5). **Organic fertilizers** can be defined as materials that are naturally occurring and have not been synthesized. Animal or plant wastes are what most people consider to be organic fertilizers and can be applied to crops directly or developed into a wide variety of other processed fertilizers. One of the attractions of these types of organic fertilizers is they are renewable and widely available. The second major category of organic fertilizers includes minerals and other materials that come directly from the earth. Minerals like sodium nitrate are commonly used in many blended organic fertilizers because they are soluble and have a high nutrient content. Like all types of mining, however, obtaining natural minerals is an extractive process and nonrenewable in the long term. Some native plant nurseries prefer organic fertilizers because they are less likely to burn crops, have lower risk of water pollution, and provide more hospitable conditions for beneficial microorganisms. The main drawbacks of organic fertilizers are that they are more

**Table 5** Comparison of attributes of organic and synthetic fertilizers

| Factor | Organic | Synthetic |
|---|---|---|
| Mineral nutrient analysis | Low | High |
| Range of mineral nutrients | All | One to many |
| Nutrient release rate | Slower | Faster |
| Compatibility with beneficial microorganisms | Yes | At low levels |
| Cost | More | Less |
| Handling | Bulkier | More concentrated |
| Ecological sustainability | Yes | No |
| Water pollution risk | Low | High |
| Other benefits | Improves soil texture and encourages soil microbes | Easier for research/control |

**Table 6** Comparison of advantages and disadvantages of two major types of synthetic fertilizers used in tropical plant nurseries

| Factor | Soluble fertilizer | Controlled-release fertilizer |
|---|---|---|
| Nutrient release rate | Very fast | Much slower – dependent on type and thickness of coating |
| Number of applications | Multiple – must be applied at regular intervals | Usually once per season, but additional top-dressing is an option |
| Uniformity of application | Good, but dependent on irrigation coverage | Can be variable if incorporated, resulting in uneven growth |
| Adjusting nutrient rates and ratios | Easy and quick | Difficult |
| Nutrient uptake efficiency | Poorer | Better |
| Leaching and pollution potential | Higher | Lower |
| Potential for fertilizer burn (salt toxicity) | Low if applied properly | Low, unless prills damaged during incorporation or in high temperatures |
| Product cost | Lower | Higher |
| Application costs | Higher | Lower |

expensive, and their lower nutrient content and solubility result in slower plant growth. **Synthetic fertilizers** are popular because they are relatively inexpensive, readily available, and have higher nutrient content compared with organic products. In populated tropical areas, synthetic fertilizers can be found at garden supply shops and through horticultural dealers, but inaccessibility and transport costs may be a limitation in remote areas. In the humid tropics, storage of synthetic fertilizers becomes a challenge because they readily absorb moisture from the air. Synthetic fertilizers can be divided into two classes: (1) soluble products that release nutrients quickly when dissolved in water and (2) slow-release or controlled-release fertilizers that release nutrients slowly over time. Both types have their advantages and disadvantages, which need to be considered before deciding upon a fertilization system (Table 6). Granular fertilizers that are used on lawns or in agriculture are not recommended for native plant nurseries.

## Fertilizer Application Rates and Methods

Fertilizer application rates depend on the growing environment and other factors such as container volume, type of growing media, growth stage (establishment, rapid-growth, hardening [described in the chapter, "▶ Planning and Managing a Tropical Nursery"]), and irrigation frequency (for example, Dumroese et al. 2011). Very small containers require lower rates applied frequently whereas larger containers can tolerate high application rates applied less frequently. In general, three types of fertilizers (liquid, controlled-release, and organic) are commonly used in nurseries.

Injecting **liquid fertilizer** solution into the irrigation system is a practice called “fertigation”. Fertilizer injectors range from simple, low-cost siphons for hand watering to sophisticated pumps for automated sprinklers. Because it can be designed to apply the proper mineral nutrients at the appropriate concentration for each growth stage, fertigation has several advantages compared with other types of fertilization. Remember that fertilizers are salts and that injecting liquid fertilizers adds to the base salinity level of the irrigation water; adding enough fertigation solution so that it barely drips from the bottoms of containers should avoid problems with salt accumulation in the medium, but if a salty crust appears at the bottom drainage holes, leaching the medium with regular irrigation water (“clear-water flush”) will reduce salt accumulation. Every fertilizer injector must be installed with a backflow preventer to eliminate the possibility that soluble fertilizer could be sucked back into the water line and contaminate drinking water.

**Controlled-release fertilizers** (CRF) can be either topdressed (sprinkled onto the surface of the medium), if care is taken to ensure that each container or cell receives an equal number of prills or incorporated into the growing medium. If growers mix CRF into their growing medium, care must be taken to ensure uniform distribution and to prevent damaging the prill coating. If the coating is fractured, then the fertilizer releases immediately causing severe salt injury. Managers can begin by using the rate recommendations provided by manufacturers (low, medium, high) if they have an idea about their particular crop; regardless, rates should be evaluated for their effect on individual plant growth and performance.

**Organic fertilizers** can be solid or liquid, commercially prepared, or natural. Composts could be incorporated into growing media but they must be fully mature to prevent fertilizer burn. One of the challenges of using liquid organic fertilizers is how to achieve the high soluble nitrogen levels necessary for rapid growth rates. High-quality nursery crops can be grown with organic fertilizers but, because their nutrient analysis is relatively low (Table 7), production schedules may have to be adjusted.

Growers need to be aware of the different nutrient requirements during each growth phase (described in the chapter, “▶ Planning and Managing a Tropical Nursery”) and adjust fertilizer prescriptions accordingly, especially during hardening. These adjustments are particularly important for nitrogen (especially the ammonium form of nitrogen), which tends to be a primary driver of plant growth and development.

Because artificial growing media, such as coir or pumice, are inherently infertile, fertilization should begin as soon as the seedlings or cuttings become established. Some commercial brands of growing media contain a starter dose of fertilizer that should be considered when determining fertilizer rates. Homemade soil mixes that have been amended with compost or other organic fertilizers may not need fertilization immediately, so observe plant growth and establish small trials to be certain.

Some tropical plant species require very little fertilizer while others must be “pushed” with nitrogen to achieve desired growth rates and reach target specifications. Gaining experience and keeping good records about growing a particular species is the best way to develop species-specific fertilizer prescriptions. Managers should never wait for their crops to show deficiency symptoms before fertilizing

**Table 7** Percentages of nitrogen, phosphorus, and potassium supplied by a variety of organic materials (Diver et al. 2008)

| Organic fertilizers | Nitrogen | Phosphorus | Potassium |
|---|---|---|---|
| Bat guano (fresh) | 10 | 3 | 1 |
| Bat guano (old) | 2 | 8 | 0 |
| Blood meal | 10 | 0 | 0 |
| Bone meal (steamed) | 1 | 11 | 0 |
| Cottonseed meal | 6 | 2 | 1 |
| Eggshells | 1.2 | 0.4 | 0.1 |
| Fish emulsion | 4 | 1 | 1 |
| Fish meal | 5 | 3 | 3 |
| Greensand | 0 | 0 | 7.0 |
| Hoof and horn meal | 12 | 2 | 0 |
| Kelp meal | 1.5 | 0.5 | 2.5 |
| Soybean meal | 7.0 | 0.5 | 2.3 |
| Worm castings | 0.5 | 0.5 | 0.3 |
| Manure: | | | |
| Cow | 2 | 2.3 | 2.4 |
| Horse | 1.7 | 0.7 | 1.8 |
| Pig | 2 | 1.8 | 1.8 |
| Sheep | 4 | 1.4 | 3.5 |
| Poultry | 4 | 4 | 2 |

because it can be difficult to alleviate the problem and produce the crop on schedule. Crop monitoring and testing, experience, and knowledge about the growth phases are the best guides for determining fertilizer timing and rates. Refer to Jacobs and Landis (2014) for further information on managing nutrition in tropical nurseries.

## Monitoring Nutrition Practices

Growers who fertigate need to periodically check the EC of the applied fertigation water and the growing medium solution. Measuring the fertigation water as it is applied to the crop can confirm that the fertilizer solution has been correctly calculated and that the injector is functioning properly. Simple handheld EC meters are fairly inexpensive. Normal readings in applied fertigation should range from 0.75 to 2.0 μS/cm. The typical range of acceptable EC values in the growing medium for most native plant species is 1.2–2.5 μS/cm. If the EC is more than 2.5, it is a good idea to leach out the salts with clean irrigation water.

Testing plant foliage is the best way to monitor plant nutrition and responses to fertilization because it provides an exact measurement of nutrients that the plant has acquired (Landis et al. 2005). By examining tissue nutrient concentrations and simultaneously monitoring plant growth, it is possible to identify if and when specific nutrients are deficient or excessive. Foliar samples must be collected in a systematic manner and sent to a reputable laboratory for processing (see section "Testing Growing Media" discussed earlier). The analyzed nutrient concentration

**Table 8** Estimated ranges of foliar nutrient levels for healthy tropical plants (based on data compiled by Drechsel and Zech (1991)) on field-grown, broad-leaved, tropical tree species). Nutrient ranges can vary greatly among species, therefore, trials are recommended to determine the best ranges for specific species

| Nutrient | Range of foliar levels in healthy plants |
|---|---|
| **Macronutrients (%)** | |
| Nitrogen | 1.5–3.5 |
| Phosphorus | 0.10–0.25 |
| Potassium | 0.60–1.8 |
| Calcium | 0.50–2.5 |
| Magnesium | 0.15–0.50 |
| Sulfur | 0.10–0.30 |
| **Micronutrients (ppm)** | |
| Iron | 50–250 |
| Manganese | 35–250 |
| Zinc | 10–40 |
| Copper | 5–20 |
| Boron | 15–50 |
| Molybdenum | 0.10–1.0 |

values can be compared with some known set of adequate nutrient values to determine which specific elements are deficient (Table 8).

Small growth trials are another good way to monitor plant nutrition and fertilization needs. These trials are especially informative for tropical plant species because so little published information is available. Detailed documentation of growing conditions, fertilizer inputs, and resulting plant response can help formulate future fertilizer prescriptions for a specific species.

### Reducing the Environmental Effects of Fertilization

Regardless of the method of fertilizer application or the type of fertilizer used, runoff of excess fertilizers is a major environmental concern. Nutrients, notably nitrate and phosphate, leach easily from container nurseries and can pollute groundwater or adjacent streams. Managers should choose the types of fertilizers and schedule their applications to minimize potential pollution concerns. Because nitrate and phosphate are extremely soluble in water, growers should irrigate only when necessary and then apply only enough water so that only small amounts drain from the containers. This approach also makes sense from an economic standpoint, because the desire is to have most of the applied fertilizer taken up by crop plants rather than lost in runoff.

## Beneficial Microorganisms

In natural ecosystems, the root systems of most plants have microbial partnerships with mycorrhizal fungi and, if applicable, with nitrogen-fixing bacteria. These partnerships enable plants to survive and grow even in harsh conditions. Without microsymbiont partners, plants remain stunted and often die. In the nursery, microsymbionts can be introduced by “inoculating” the root systems of plants with the appropriate beneficial microorganisms to form effective partnerships. Plants that have been inoculated in the nursery will be outplanted with microbial partnerships in place and often are better able to survive in the field.

## Nitrogen-Fixing Bacteria

Nitrogen (N), one of the most important nutrients for plant growth, is abundant in the Earth’s atmosphere as $N_2$, but it must be converted to either nitrate ($NO_3^-$) or ammonium ($NH_4^+$) before most plants can use it. In nature, $N_2$-fixing bacteria convert (“fix”) $N_2$ from the air into a form usable to plants. When the growing roots of a plant capable of forming a partnership with rhizobia come in contact with a compatible strain of $N_2$-fixing bacteria in soil or growing media, the rhizobia bacteria will enter (“infect”) the roots. Nodules then form on the plant’s roots where the contact occurred. The bacteria live and multiply in the nodules on the host root system, providing N from the atmosphere to their plant host. Two types of $N_2$-fixing bacteria form symbiotic partnerships with plants: rhizobia (consisting of several genera) and the genus *Frankia*.

Inoculants are live $N_2$-fixing bacteria cultures that are applied to seeds or young plants, imparting the beneficial bacteria to the plant’s root system. Inoculants for $N_2$-fixing bacteria tend to be very specialized. Care must be taken to select appropriate and effective $N_2$-fixing partners for specific plant species. Pure-culture inoculants of $N_2$-fixing bacteria usually come in small packets of finely ground peat moss. Not all manufactured inoculants are selected and matched to native species, however, so be sure to check the source. Manufactured products usually come with application instructions; these directions need to be followed. Crude inoculant can be made from nodules collected from the roots of healthy, established host plants. For rhizobia, a brown, pink, or red color inside is usually a good indicator that the millions of bacteria in the nodule are actively fixing $N_2$. For *Frankia*, desirable nodules will be white or yellow inside. Grey or green nodules should be avoided, because they likely are inactive. As soon as possible after collection, put the nodules in a blender with clean, chlorine-free water. About 50–100 nodules blended in about 1 L of water are sufficient to inoculate about 500 plants.

Inoculant for $N_2$-fixing bacteria is commonly applied when seedlings are emerging, usually within 2 weeks of sowing, or just after cuttings have formed roots. The inoculant is watered into the growing media or soil in which seedlings are growing. After 2–6 weeks, these four signs indicate that the plant has formed a symbiotic partnership with $N_2$-fixing bacteria: (1) plants begin to grow well and are deep green despite the absence of added $N_2$ fertilizer (Fig. 12a); (2) root systems give off a faint but distinctive ammonia-like scent; (3) nodules are visible on the root system; and (4) when a nodule is broken open, its inside is pink, red, or brown (for rhizobia) (Fig. 12b), or yellow or white (for *Frankia*).

**Fig. 12** The 6-week-old native Acacia koa seedlings (*right*) were inoculated with rhizobia at 2 weeks of age; the seedlings on the *left* were not inoculated (**a**). Nodules from an Acacia koa seedling showing pink inside, signifying nitrogen is being fixed (**b**) (Photo (**a**) by Craig R. Elevitch and photo (**b**) by J.B. Friday)

## Mycorrhizal Fungi

“Myco” means “fungus” and “rhiza” means “root;” thus “mycorrhizae” means “fungus-roots.” Most of the world’s plants depend on their partnership with mycorrhizal fungi to thrive. The host plant’s roots provide a substrate for the fungi and supply food in the form of simple carbohydrates. In exchange, the mycorrhizal fungi offer increased water and nutrient update, stress and disease protection, and increased vigor and growth.

Mycorrhizal fungi are not “one size fits all,” but they often are “one size fits many.” Also, one plant can partner simultaneously with several species of mycorrhizal fungi, and a plant may change partners over time as it grows and adapts to its environment (Amaranthus 2010). Three types of mycorrhizae are important to tropical native plant nurseries.

- **Arbuscular Mycorrhizal (AM) Fungi** – AM fungi are essential for most tropical trees and other plants and for many annual crops and grasses. AM fungi are not visible on plant roots to the unaided eye and must be observed under a microscope. Inoculant for AM fungi is sometimes collected from root systems of AM host plants or soil underneath them and incorporated into growing media. Another method is pot culture inoculant, in which a specific AM fungus species is acquired either commercially or from a field site as a starter culture and then incorporated into a sterile growing medium. A host plant, such as corn, sorghum, clover, or an herbaceous native plant, is grown in this substrate. After the host plant roots have spread throughout the medium, their shoots are removed and the substrate, now rich in roots, spores, and mycelium, is chopped up and incorporated into fresh growing medium (Habte and Osorio 2001, Miyasaka et al. 2003). Commercial sources of AM fungi inoculant are also available, usually containing several species or strains.
- **Ectomycorrhizal (ECM) Fungi** – ECM fungi only affect a small percentage of tropical species, including pines, eucalypts, poplars, oaks, dipterocarps, and some legumes. Nurse plants and soil spores have been used historically, while spores collected from the fruiting bodies of mushrooms and pulverized in a blender or pure culture inoculant in a peat-based carrier are usually recommended for nurseries.
- **Ericoid Mycorrhizal (ERM) Fungi** – Plants that form partnerships with ericoid mycorrhizal fungi are able to grow in exceptionally nitrogen-poor soils and harsh conditions, including bogs, alpine meadows, tundra, and even in soils with high concentrations of certain toxic metals. Similar to ECM fungi and AM fungi, ericoid mycorrhizal fungi must come in contact with the host plants roots to form partnerships. Ericoid mycorrhizal inoculant is available as commercial cultures or from soil near healthy host plants. The product or soil is mixed into nursery growing medium.

## Problem Prevention and Holistic Pest Management

Holism is the theory that systems are not a group of isolated parts, but rather should be viewed as a whole. Holistic pest management is an integrated and preventative approach that considers the overall health of the plant and the nursery environment to prevent problems and to manage them wisely if they arise. Holistic pest management includes problem prevention through cultural mechanisms, early detection and evaluation, and management measures as needed to suppress pests and ecologically balance their populations. Holistic pest management can reduce reliance on pesticides (Dumroese et al. 1990). For holistic pest management, it is important to remember the “disease triangle” concept that illustrates the interrelationships among the pest, host, and environment. All three factors are necessary to cause biotic disease.

The holistic approach to nursery pest management involves a series of four interrelated practices, which ideally function together (modified from Wescom 1999):

- **Problem Prevention through Cultural Measures –** includes good sanitation, proper scheduling, management of the nursery environment, and promotion of plant health through proper irrigation and fertilization.
- **Problem Detection and Diagnosis –** is accomplished through regular monitoring, recordkeeping, and accurate problem identification.
- **Problem Management –** includes, if necessary, timely and appropriate pest suppression measures and balancing pest populations with beneficial organisms and pest predators.
- **Ongoing Process Evaluation –** is to learn from experience by assessment and improved effectiveness of pest management approaches.

A complete description of holistic pest management is beyond the scope of this chapter. For a good overview of this concept, consult Landis et al. (1989b, 2008) and Dumroese (2012), and for specific focus on tropical nurseries, refer to Landis et al. (Landis et al. 2014c).

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## References

Amaranthus M (2010) Personal communication. Mycorrhizal Applications, Grants Pass, Oregon, USA

Buamscha G, Altland J (2005) Pumice and the Oregon nursery industry. Digger 49(6):18–27

Bunt AC (1988) Media and mixes for container grown plants. Unwin Hyman, London, p 309

Carrion C, Abad M, Fornes F, Noguera V, Maquieira A, Puchades R (2006) Leaching of composts from agricultural wastes to prepare nursery potting media. Acta Horticult 697:117–124

Cayanan DF, Zheng Y, Zhang P, Graham T (2008) Sensitivity of five container-grown nursery species to chlorine in overhead irrigation water. HortScience 43:1882–1887

Davis AS, Jacobs DF, Overton RP, Dumroese RK (2008) Influence of irrigation method and container type on growth of Quercus rubra seedlings and media electrical conductivity. Native Plants Journal 9:4–12

Diver S, Greer L, Adam KL (2008) Sustainable small-scale nursery production. National Center for Appropriate Technology (NCAT) Sustainable Agriculture Project, Butte. https://attra.ncat.org/attra-pub/summaries/summary.php?pub=60. Accessed 11 Nov 2011

Drechsel P, Zech W (1991) Foliar nutrient levels of broad-leaved tropical trees: a tabular review. Plant Soil 131:29–46

Dumroese RK (2012) Integrated nursery pest management. In: Cram MM, Frank MS, Mallams KM (eds) Forest nursery pests (tech cords). US Department of Agriculture, Forest Service, Agriculture Handbook 680, Washington, DC, pp 5–12

Dumroese RK, Wenny DL, Quick KE (1990) Reducing pesticide use without reducing yield. Tree Planters' Notes 41(4):28–32

Dumroese RK, James RL, Wenny DL (2002) Hot water and copper coatings in reused containers decrease inoculum of *Fusarium* and *Cylindrocarpon* and increase Douglas-fir seedling growth. HortScience 37:943–947

Dumroese RK, Pinto JR, Jacobs DF, Davis AS, Horiuchi B (2006) Subirrigation reduces water use, nitrogen loss, and moss growth in a container nursery. Native Plants Journal 7:253–261

Dumroese RK, Luna T, Landis TD (eds) (2008) Nursery manual for native plants: volume 1, a guide for tribal nurseries. US Department of Agriculture, Forest Service, Agricutlure Handbook 730, Washington, DC, p 302

Dumroese RK, Davis AS, Jacobs DF (2011) Nursery response of *Acacia koa* seedlings to container size, irrigation method, and fertilization rate. J Plant Nutr 34:877–887

Dumroese RK, Landis TD, Luna T (2012) Growing native plants in nurseries: basic concepts. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-274, Fort Collins, p 84

Evans J (1996) Plantation forestry in the tropics. Clarendon, Oxford

Evans MR, Konduru S, Stamps RH (1996) Source variation in physical and chemical properties of coconut coir dust. HortScience 31:965–967

Grubinger V (2007) Potting mixes for organic growers. University of Vermont Extension, Brattleboro. http://www.uvm.edu/vtvegandberry/factsheets/pottingmix.html. Accessed 21 Aug 2011

Habte M, Osorio NW (2001) Arbuscular mycorrhizas: producing and applying arubscular mycorrhizal inoculum. Honolulu, HI: University of Hawai‘i, College of Tropical Agriculture and Human, p 47

Handreck KA, Black ND (1984) Growing media for ornamental plants and turf. Kensington, Australia: New South Wales University Press, p 401

Jacobs DF, Landis TD (2014) Plant nutrition and fertilization. In: Wilkinson KM, Landis TD, Haase DL, Daley BF, Dumroese RK (eds) Tropical nursery manual: a guide to starting and operating a nursery for native and traditional plants. US Department of Agriculture, Forest Service, Agriculture Handbook 732, Washington, DC, pp 233–250

Jacobs DF, Landis TD, Luna T, Haase DL (2014) Propagation environments. In: Wilkinson KM, Landis TD, Haase DL, Daley BF, Dumroese RK (eds) Tropical nursery manual: a guide to starting and operating a nursery for native and traditional plants. US Department of Agriculture, Forest Service, Agriculture Handbook 732, Washington, DC, pp 89–99

Jaenicke H (1999) Good tree nursery practices: practical guidelines for research nurseries. International centre for research in agroforestry. Majestic Printing Works, Nairobi, p 93

Johnson P (1968) Horticultural and agricultural uses of sawdust and soil amendments. Paul Johnson, National City, p 46

Landis TD (1995) Improving polybag culture for sustainable nurseries. Forest Nursery Notes (July 1995) pp 6–7

Landis TD, Dumroese RK (2006) Monitoring electrical conductivity in soils and growing media. Forest Nursery Notes (Summer 2006), pp 6–10

Landis TD, Dumroese RK (2011) Using organic fertilizers in forest and native plant nurseries. Forest Nursery Notes 31(2):9–18

Landis TD, Morgan N (2009) Growing media alternatives for forest and native plant nurseries. In: Dumroese RK, Riley LE (eds) National proceedings: forest and conservation nursery associations – 2008 (tech coords). US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Proceedings RMRS-P-58, Fort Collins, pp 26–31

Landis TD, Wilkinson KM (2014) Water quality and irrigation. In: Wilkinson KM, Landis TD, Haase DL, Daley BF, Dumroese RK (eds) Tropical nursery manual: a guide to starting and operating a nursery for native and traditional plants. US Department of Agriculture, Forest Service, Agriculture Handbook 732, Washington, DC, pp 207–230

Landis TD, Tinus RW, McDonald SE, Barnett JP (1989a) The container tree nursery manual. Volume 4, seedling nutrition and irrigation. US Department of Agriculture, Forest Service, Agriculture Handbook 674, Washington, DC, p 119

Landis TD, Tinus RW, McDonald SE, Barnett JP (1989b) The container tree nursery manual. Volume 5, the biological component: nursery pests and mycorrhizae. US Department of Agriculture, Forest Service, Agriculture Handbook 674, Washington, DC, p 171

Landis TD, Haase DL, Dumroese RK (2005) Plant nutrient testing and analysis in forest and conservation nurseries. In: Dumroese RK, Riley LE, Landis TD (tech coords) National proceedings, forest and conservation nursery associations – 2004. US Department of Agriculture, Forest Service, Rocky Mountain Research Station. Proceedings RMRS-P-35, Fort Collins, pp 76–83

Landis TD, Luna T, Dumroese RK (2008) Holistic pest management. In: Dumroese RK, Luna T, Landis TD (eds) Nursery manual for native plants: a guide for tribal nurseries. Volume 1: nursery management. USDA Forest Service. Agriculture Handbook 730, Washington, DC, pp 262–275

Landis TD, Jacobs DF, Wilkinson KM, Luna T (2014a) Growing media. In: Wilkinson KM, Landis TD, Haase DL, Daley BF, Dumroese RK (eds) Tropical nursery manual: a guide to starting and operating a nursery for native and traditional plants. US Department of Agriculture, Forest Service, Agriculture Handbook 732, Washington, DC, pp 101–121

Landis TD, Jacobs DF, Wilkinson KM, Luna T (2014b) Containers. In: Wilkinson KM, Landis TD, Haase DL, Daley BF, Dumroese RK (eds) Tropical nursery manual: a guide to starting and operating a nursery for native and traditional plants. US Department of Agriculture, Forest Service, Agriculture Handbook 732, Washington, DC, pp 123–139

Landis TD, Luna T, Wilkinson KM, Dumroese RK (2014c) Problem prevention and holistic pest management. In: Wilkinson KM, Landis TD, Haase DL, Daley BF, Dumroese RK (eds) Tropical nursery manual: a guide to starting and operating a nursery for native and traditional plants. US Department of Agriculture, Forest Service, Agriculture Handbook 732, Washington, DC, pp 273–291

Lovelace W, Kuczmarski D (1994) The use of composted rice hulls in rooting and potting media. Int Plant Propag Soc Comb Proc (1992) 42:449–450

Miller JH, Jones N (1995) Organic and compost-based growing media for tree seedling nurseries. World Bank Tech. Paper No 264, Forestry Series. The World Bank, Washington, DC, 75 p

Miyasaka SC, Habte M, Friday JB, Johnson EV (2003) Manual on arbuscular mycorrhizal fungus production and inoculation techniques. University of Hawai'i at Mānoa, College of Tropical Agriculture and Human Resources, Honolulu, p 4

Newman J (2007) Core facts about coir. Greenhouse Manag Proc 27(2):57

Noguera P, Abad M, Noguers V, Puchades R, Maquieira A (2000) Coconut coir waste: a new and environmentally friendly peat substitute. Acta Hort 517:279–286

Pinto JR, Chandler R, Dumroese RK (2008) Growth, nitrogen use efficiency, and leachate comparison of subirrigated and overhead irrigated pale purple coneflower seedlings. HortScience 43(3):897–901

Robbins J (2011) Irrigation water for greenhouses and nurseries. Publication FSA6061. University of Arkansas, Horticulture Department, Little Rock, p 6

Stetson LE, Mecham BQ (2011) Irrigation, 6th edn. Irrigation Association, Falls Church, p 1089

Timmer VR, Parton WJ (1982) Monitoring nutrient status of containerized seedlings. In: Proceedings, Ontario ministry of natural resources nurseryman's meeting, 1982 June, Thunder Bay/Toronto, Ontario Ministry of Natural Resources, pp 48–58

Wescom RW (1999) Nursery manual for atoll environments. SPC/UNDP/AusAID/FAO Pacific Islands forests and trees support programme, RAS/97/330. Working Paper 9. p 53

Whitcomb CE (2003) Plant production in containers II. Lacebark Publications, Stillwater, p 129, 1

Wilkinson KM, Landis TD, Haase DL, Daley BF, Dumroese RK (eds) (2014) Tropical nursery manual: a guide to starting and operating a nursery for native and traditional plants. US Department of Agriculture, Forest Service. Agriculture Handbook 732, Washington, DC, p 377