

Conducting Seedling Stocktype Trials: A New Approach to an Old Question

Jeremiah R. Pinto, R. Kasten Dumroese, Anthony S. Davis,
and Thomas D. Landis

ABSTRACT

Seedlings for reforestation and restoration come in many shapes and sizes, i.e., a variety of stocktypes. With so many choices available, land managers commonly ask which stocktype will best meet their management objectives. For years, stocktype studies have been initiated in search of an answer to this question, but few have been done without some degree of confounding. Past studies often confounded seed sources, nurseries, and culturing regimes, and/or failed to address differences in initial seedling quality, which sometimes led to inappropriate conclusions. This article reviews the reasoning behind stocktype studies, reviews common pitfalls of past studies, and suggests some key considerations to making future stocktype studies a viable resource to the practicing forester.

Keywords: target plant concept, outplanting, seedling quality, container, bareroot

Since the inception of reforestation, the availability and type of seedlings has greatly increased, as has the debate over which type of seedling works best. Over time, nursery managers have effectively learned how to manipulate seedling characteristics during nursery production to maximize survival and growth for the benefit of the practicing forester. The first major shift in seedling type was from bareroot seedlings to bareroot transplants, achieving larger stock with more fibrous root systems. Next, the layering of other cultural practices, including the use of containers and the use of both containers and bareroot beds, created even larger seedlings faster. These innovations resulted in an ever-increasing number of seedling types and cultural methods thereby adding to the complexity of seedling type nomenclature and choice. Nomenclature was simplified with the referential term “stocktype,” which describes “how” a seedling is pro-

duced and consequently conjures up a visual reference of what the seedling should look like before outplanting. However, the age-old question of which stocktype will perform the best for the project at hand remains pertinent.

Historically, foresters drew on their personal experience, the experience of their peers, advice from nursery managers, and literature to help guide their choices. The Target Seedling Concept—later termed Target Plant Concept (TPC) to include plant materials other than seed propagated stocktypes—was proposed to link the stocktype decisionmaking process to three simple ideas: (1) the desired plant material is determined by factors on the outplanting site, (2) the nursery manager and client are partners, and (3) seedling quality is paramount (Rose et al. 1990, Landis and Dumroese 2006, Landis 2009, Landis et al. 2010). From these ideas, the TPC generates six interrelated steps that help define target plant

materials for a site. The defined target plant material can then be produced by the nursery manager through manipulation of the growing environment to influence resulting phenotype. By varying, e.g., bareroot seedbed density or container type, seedling phenotype can be modified, even among seedlings coming from the same seed source grown the same year (Endean and Carlson 1975, Simpson 1991, Pinto et al. 2008).

Phenotypic variation of seedlings (e.g., height, branching pattern, root collar diameter, or the size and shape of root systems) has resulted in a large body of literature identifying survival and growth advantages under certain outplanting conditions. For example, where seedlings experience drought, typical study results show that coniferous, deciduous, or restoration seedlings with larger or longer root systems have better survival or growth (Amidon et al. 1982, Rose et al. 1997, Chirino et al. 2008). Seedlings with a well-balanced ratio of shoot biomass to root biomass (shoot-to-root ratio [S:R]) can also be beneficial on droughty sites. Cregg (1994) suggests optimum seedling S:R, where shoots are not so large they create water deficit through large transpirational surface areas, and shoots are not so small that they lack the photosynthetic capacity to produce carbohydrate reserves to endure long periods of drought. When vegetative competition is a problem on a site, seedlings that are larger in size are found to be effectively competitive for

Received September 14, 2010; accepted January 10, 2011.

Jeremiah R. Pinto (jpinto@fs.fed.us) is research plant physiologist, and R. Kasten Dumroese (kdumroese@fs.fed.us) is research plant physiologist, US Forest Service, Rocky Mountain Research Station, 1221 South Main Street, Moscow, ID 83843. Anthony S. Davis (asdavis@uidaho.edu) is assistant professor, Department of Forest Ecology and Biogeosciences, University of Idaho, Moscow, ID 83844. Thomas D. Landis (nurseries@aol.com) is forest and native plant nursery consultant, 3248 Sycamore Way, Medford, OR 97504. The authors thank David L. Wenny, John D. Marshall, and Robert L. Mahler for contributions toward the work that led to this article.

What is a stocktype?

In reforestation and restoration, stocktype essentially describes a seedling's age and method of production. The designation inexactly implies the seedling's relative size and typically conveys little information about physiology. Over the years, stocktype nomenclature has involved simple naming such as "Styro-20" (a 20 in³ container seedling) or "1+0" (a one-year-old bareroot seedling), to more complex versions that require more intimate knowledge of the jargon, such as "Fdc PSB 412A 1+0 Sp" that describes species (coastal Douglas-fir), production method (Styrofoam container), container size (4 cm diameter × 12 cm depth × 364 plants per square meter), seedling age (one year), and season of sowing (spring). Many different stocktypes exist today and the list of jargon describing them is equally long, making it difficult to understand the nuances among resulting stocktypes.

aboveground resources such as light (Overton and Ching 1978, Newton et al. 1993, Thiffault et al. 2003). Larger stocktypes tend to maintain their size advantage over time when compared with smaller stocktypes (Simpson 1994, Jacobs et al. 2005), which ostensibly leads to the conclusion that large, robust, and well-branched seedlings will stand up to physical damage, such as snowpack effects, vegetation press, trampling, and animal browse, after planting (Haase et al. 2006, Rose and Haase 2006).

Why Conduct a Stocktype Study?

The first stocktype trials were probably done because prudent foresters were interested in how they can improve seedling survival and growth as well as see how new products measured up against the status quo. This is especially true for reforestation and restoration projects with unique planting conditions; e.g., a site might be especially dry, extremely rocky with little topsoil, or might have saline conditions in the upper soil profile. Site preparation may also impose some unique challenges on existing site limitations, as in some cases, herbicide use or burn treatments may no longer be allowed to control competing vegetation (Lamhamedi et al. 1996). Concomitantly, maximizing seedling survival and subsequent growth per dollar spent—finding out which

stocktype provides the best "bang for the buck"—will always be a legitimate reason to conduct a stocktype study. For instance, is it worth it to pay more, in materials and planting costs, for a stocktype with a larger, more robust root system? Or perhaps long-term management objectives, which may dictate seedling density on the outplanting site (South 2006), are the guiding factor in stocktype choice. Some reforestation and restoration sites might be exposed to increasingly hotter and drier environmental conditions making establishment and growth of planted seedlings difficult; the use of new or different stocktypes may be an additional tool used to increase seedling survival. One final reason for conducting stocktype studies is that trees are not the only seedlings being planted to meet a myriad of sustainable forestry goals. Other native plant species have unique configurations of root and shoot growth form that will ultimately require stocktype testing. Needless to say, the appropriate stocktype, for the appropriate species, in a unique planting situation, could easily warrant a small study to determine what stocktype may work best to maximize outplanting success. Currently, less funding is available for this type of work, particularly with changes in forest ownership and management objectives—such as timber investment management organizations and real estate investment trusts. Therefore, prudent managers need to know that the small amount of resources being spent on research and design yield the best results to help them make correct decisions.

What Can We Learn from Previous Stocktype Studies?

To properly conduct a stocktype study, existing literature should be a guide for setup, with care to identify the pitfalls of past studies. A closer look at previous stocktype studies reveals, unfortunately, several sources of potential confounding variables: mixing seed sources, using different nurseries and culturing regimes; statistical design error; single-year analyses; and failure to address seedling quality attributes (i.e., morphology, physiology, or performance potential; Landis et al. 2010). In many cases, these confounded variables make the subsequent conclusions tenuous. One might argue that allowing such confounding is acceptable to provide broad inference, such as container seedlings are better than bareroot seedlings, or 1 + 1s are better than 2 + 0s. This, however, runs contrary to the TPC and to the paradigm that seedling quality is only proved on the outplanting site. Indeed, con-

trolling confounding could perhaps lead to greater inference because of better foundational knowledge/understanding of how nursery practices influence seedling quality.

One common source of confounding is not growing all the stocktypes with the same seed source. This should immediately raise "red flags" because basic biology and the literature tell us we can expect differences in seedling performance based on seed source and genotypes. Any given study can use more than one seed source, as long as all stocktypes are represented by each source or an appropriate experimental design is used to allow for appropriate analysis and interpretation. Another common problem is comparing stocktype A (e.g., bareroot 1 + 1) grown in one nursery with stocktype B (e.g., bareroot 2 + 0) grown in a different nursery. This approach is flawed because differences in seedling propagation locations (i.e., providing different levels of temperature, light, humidity, CO₂, nutrients, and water) affect seedling performance (Paterson 1997, Pinto et al. 2006). In addition to a nursery's unique growing conditions, nurseries can vary significantly in the culturing regime used to produce stock (Figure 1), thereby having a significant impact on seedling phenotype and seedling quality. This is particularly true for container nurseries.

In stocktype trials, when the stocktypes are from different nurseries or are cultured within a single nursery with a single cultural regime, the stocktype trials may no longer be evaluating the intrinsic nature of the stocktype, but rather evaluating the cultural practices used to produce the stocktype. To prove this point, Pinto (2005) investigated the differences among several stocktypes grown in two nurseries using the same seed source; additionally, Pinto (2005) explored the possibility of growing different stocktypes uniformly (for the purposes of subsequent stocktype studies) within a single nursery. The culturing regime within one nursery was tailored for each stocktype according to fertilizer and irrigation to maximize physiological uniformity among container types, while the other nursery used only operational growing regimes to produce the same variety of stocktypes. Smaller variation was seen in the S:R of seedlings used from the four stocktypes cultured under custom growth regimes versus the S:R of the four stocktypes cultured under one growing regime (Table 1). These differences in initial S:R could mean a noteworthy difference in field performance, especially considering implications for seedling survival in drought conditions (Cregg 1994). In the worst case scenario,

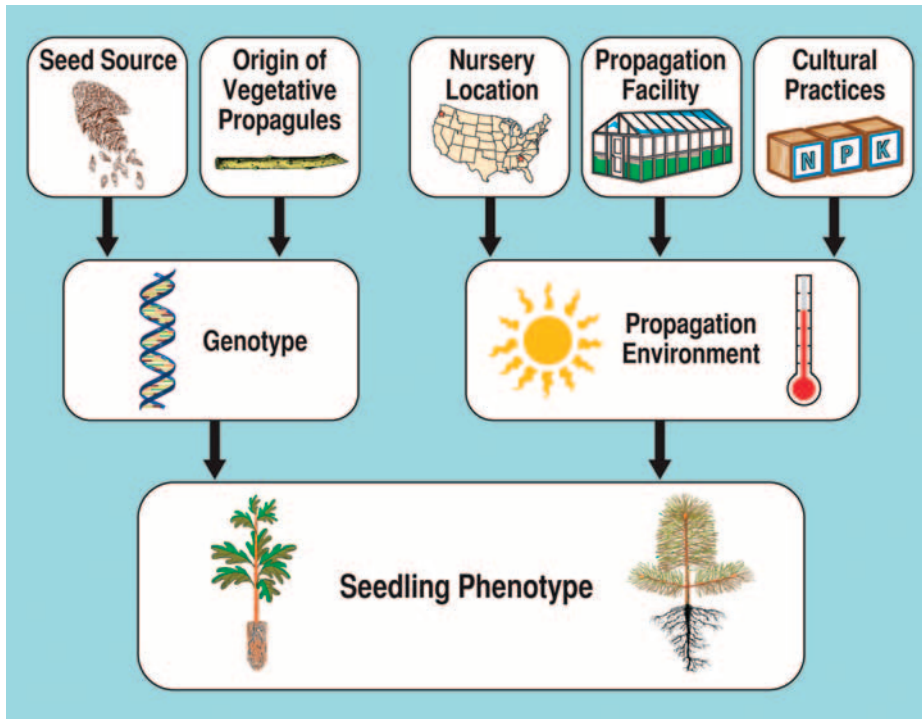


Figure 1. A change or modification to any one of the primary variables of the propagation environment or genotype will have an effect on a seedling's phenotype and its relative quality.

if a few stocktypes were used from both facilities, mean S:R could vary as much as 67% (1.5 versus 2.5) among stocktypes; a difference this large can have significant physiological (Burdett 1990) and survival implications (Cregg 1994). Pinto's (2005) data also illustrated morphological (height and biomass) and physiological differences (foliar nitrogen concentration, cold hardiness levels, and water-use efficiency) that can arise between similar

stocktypes produced in the different nurseries (Table 1). This reinforces the idea that seedling quality and performance potential can be vastly different among seedlings taken from different nurseries (and used in stocktype studies), even when they are produced from the same seedlot over the same growing season. These examples illustrate differences within a stocktype produced at two respective nurseries, but, more importantly, were the differ-

ences or similarities that could evolve within one greenhouse. Seedlings that were cultured optimally according to their specific container type showed greater uniformity in S:R and percent nitrogen concentration, two variables associated with seedling survival and growth (van den Driessche 1988, Cregg 1994, Rikala et al. 2004).

Although stocktype studies can be measured for a number of years, they often only capture the unique outplanting conditions for the establishment year. It is within that 1st year that a seedling can face the largest obstacles to survival (Burdett 1990, Grossnickle 2005). Whether or not a stocktype study captures the desired outplanting conditions (harsh or ideal) is left up to nature. Some years might be dry (Amidon et al. 1982), while others may pose mesic conditions yielding no specific survival advantages gained by stocktype (Pinto et al. 2011). Although we discuss alternatives to single-year analyses later, it is well known that this will always be an issue when conducting stocktype studies.

The Burdett (1990) model of seedling establishment outlines a feedback relationship that links seedling physiology to outplanting success (Figure 2). According to the model, any compromise to seedling physiology or quality can disrupt the feedback relationship and compromise a seedling's ability to survive and grow on any given plantation site. For example, mineral deficiency can limit photosynthesis and root growth; hydraulic limitations can influence plant water potential; and reductions in cold hardiness leave plants susceptible to frost damage that

Table 1. Styrofoam container specifications and seedling attributes of *Pinus ponderosa* seedlings used in a study by Pinto (2005). For each stocktype, seedlings were produced in two nursery facilities (F1, customized stocktype regimes; F2, noncustomized stocktype regimes).

Container specifications	Stocktypes							
	160/90 ^a (315B) ^b		112/105 (415B)		160/120 (323A)		112/166 (420A)	
Cells per container	160		112		160		112	
Diameter (cm)	3		3.6		3		3.6	
Depth (cm)	15.1		15.2		22.7		20.3	
Volume (cm ³)	90		103		120		164	
Density (per m ²)	756		530		756		530	
Seedling attributes	F1	F2	F1	F2	F1	F2	F1	F2
Height (cm)	18.9	20.2	19.0	19.9	19.6	19.5	20.7	19.7
Biomass (g)	2.6	3.5	3.3	4.4	2.6	4.0	3.6	5.7
S:R	1.7	2.5	1.6	2.4	1.5	2.0	1.6	2.0
Percent nitrogen	2.3	2.4	2.2	2.2	2.3	2.3	2.3	2.3
LT ₅₀ (°C) ^c	-23.6	-23.9	-27.0	-22.3	-26.7	-24.0	-25.5	-21.7
W _i (μmol mol ⁻¹) ^d	43.7	70.8	44.7	70.8	39.7	69.8	39	64.2

^a US stocktype designation.

^b Canadian stocktype designation.

^c Cold hardiness measured as the lethal temperature at 50% seedling mortality.

^d Intrinsic water-use efficiency.

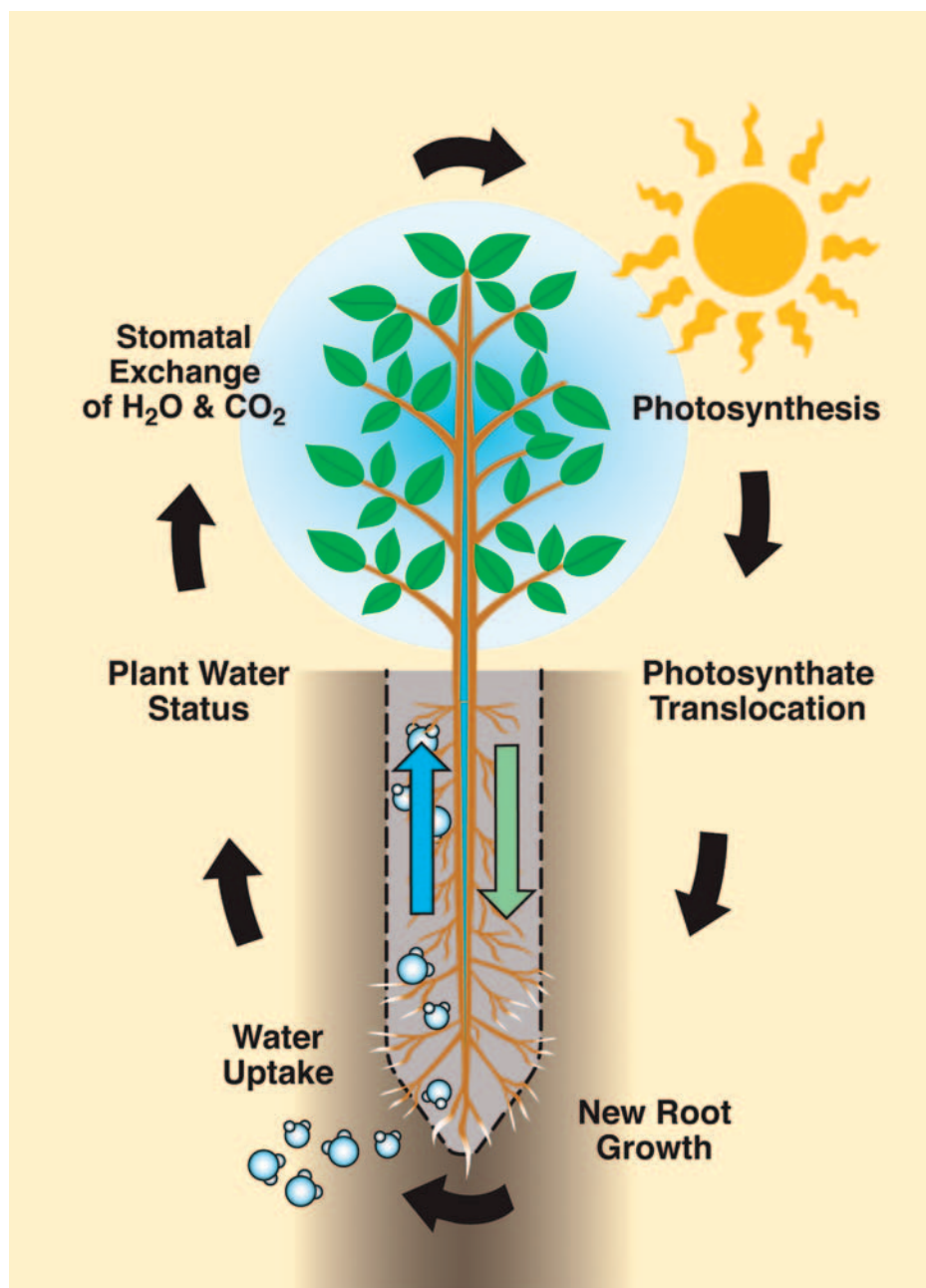


Figure 2. The mutual dependence and feedback relationship of root growth, plant water status, and photosynthesis are central processes in seedling establishment and are intimately tied to a seedling's initial quality and its physiological status immediately after outplanting. A compromise in any one of these areas can cause a break in the feedback relationship, resulting in reduced seedling growth or mortality (adapted from Burdett 1990).

can then reduce potential photosynthetic material. Now consider a stocktype study viewed through the lens of the establishment model. If a seedling quality attribute is compromised in a stocktype, its establishment and growth is limited; consequently, the stocktypes' reduced outplanting performance will bias the study's results in favor of the other stocktypes (Hobbs 1984). An example of where reduced seedling quality can

affect study results can be seen in Lamhammedi et al. (1996) with container black spruce seedlings. In their experiment, they concluded that poor seedling quality in the largest stocktype negatively affected their outplanting performance results. Although not specifically stated, seedling quality differences were likely attributed to the use of stocktypes from different nurseries and the differences in the nursery culture of "normal

production run" stock versus "test productions for the large seedlings." If stocktype studies do not explicitly state potential bias within their results, land managers using the studies as guides may implement the wrong stocktype selections, thereby compromising maximal survival and growth.

The seedling quality argument is important; however, determining which attributes to measure to deem a level playing field among the stocktypes being tested can be difficult, time-consuming, and expensive. Attributes for assessing quality include, but are not limited to, mineral nutrient status, carbohydrate status, cold hardiness, root growth potential, water status, and morphological characteristics (Duryea 1984, Duryea and McClain 1984). Although many emphasize the importance of seedling morphology and physiology (Sutton 1979, Tinus and Owston 1984, Duryea 1985, Puttonen 1989), the combination of these criteria is rarely used in stocktype comparisons (Hobbs 1984) because of the lack of a rapid, encompassing, physiological test. Thus, morphological grading criterion is the norm for classifying quality seedlings before outplanting studies rather than combining that with several physiological tests; a combination of the currently used practices would probably be most appropriate. Proper morphological and physiological attribute selection, as deemed appropriate by the TPC, should be done according to research objectives and current literature.

How Can Future Stocktype Studies Be Improved?

Foresters will always need stocktype studies because unique variables in reforestation and restoration create questions as to which stocktype is most appropriate. The key to finding the appropriate stocktype is to learn from past mistakes and answer the question in the best means possible. Often, the questions being answered will be of the operational or applied nature: "What is the maximal survival and growth that can be achieved per dollar spent?" Conversely, on a more detailed note, practicing foresters or scientists might want to know the influence of more specific variables, such as root or container volume, root depth, density effects, site treatments, site conditions, or climate change variables. In either case, providing attention to some key considerations—such as seed sources, propagation environments, study design, and outplant-

Table 2. A stocktype study checklist: Key considerations to minimize confounding variables.

Identify the stocktype study objective—Isolate the variable being tested to reduce error
Genetic sources—All stocktypes grown with the same genetic source(s)
Propagation environments—Should have similar edaphic, temperature, light, and vapor pressure deficit ^a
Seedling physiology/quality—Should be uniform across stocktypes
a. Mineral nutrition is adequate
b. Irrigation regimes adjusted according to stocktype
c. Hardening and storage regimes should be sufficient and similar
Study design—Use a solid statistical design for appropriate analysis and interpretation
Outplanting—Include multiyear analyses to account for year-to-year variation or use controlled environments (growth chambers or controlled field conditions)

^a Except when the study involves both bareroot stock and greenhouse container stock, whereby the different propagation environments and different cultural practices are an inherent part of the stocktype study.

ing conditions—will yield better answers to today's questions (Table 2).

Seed Sources

Most reforestation and restoration projects begin with seeds and this is the starting point when considering a good design for a stocktype study. For most trials, the correct step is as simple as using the same source across all stocktypes being tested. Many seed sources can be incorporated into a study as long as they are represented across all stocktypes and treatments to reduce error.

Propagation Environments

All planting stock should be obtained from one nursery and, ideally, have them propagated in the same facility or same seedbed under the same environmental conditions. Minimizing variations in seedling quality caused by different soil, light, temperature, and vapor pressure gradient regimes is the key objective, but also requires attention to cultural practices that influence those variables (Figure 1). Seedling phenotypes, along with their physiological status and performance potential, are determined in this step and are the building blocks for the seedling's 1st year of outplanting survival and growth (Burdett 1990). Testing stocktypes for uniform seedling quality before installing a stocktype study can be time-consuming and expensive and will therefore always be a limitation. We know, however,

that using uniform culturing regimes across stocktypes, i.e., customized and optimized for each, offers the best chance at leveling seedling quality before outplanting (Pinto 2005). Within the culturing regimes, it is important to ensure that mineral nutrition is adequate for each stocktype, and periodic foliar analysis during culturing will help the nursery manager adjust rates to ensure that plant nutrition is at its targeted optimum. Because drought stress in the nursery can affect seedling growth after outplanting (van den Driessche 1991a, 1991b), it is also important to custom irrigate each stocktype. This can easily be done operationally using gravimetric weights in a container nursery (Landis et al. 1989) or by measuring plant moisture stress in bareroot beds (Landis et al. 2010). If a study is incorporating both bareroot and container stock, it would be best to irrigate both stocktypes using a moisture metric that can be applied to both—plant moisture stress, volumetric soil water content, or soil water potential are all feasible options.

Stocktype Variables

When designing a container stocktype study to answer specific questions, such as what advantages particular densities, volumes, or depths might offer, it is important to remember that these characteristics are usually confounded and impossible to separate under normal "operational" methods. That is, when trying to isolate container volume attributes with operational nursery containers, changes in seedling density usually will occur. Is this a part of the study design? Is the goal to determine what the operational standard offers or what a specific stocktype attribute offers? In some cases, modifications to operational container types are needed to help isolate the variable in question. For example, to mitigate density effects, it is simple to sow a high-density propagule tray at a lower density to match other lower-density trays in the study, but of course the reverse is not possible. Although neither operational standard nor specific stocktype attribute approach is wrong, it is important to identify what is being tested to reduce error in the conclusion.

Study Design

Another way to reduce error is to choose a robust statistical design. In 1974, Owston and Stein suggested a method for comparing stocktypes in an attempt to homogenize statistical designs, comparison

methods, and data interpretation. Not surprisingly, they offer many tips to get the best results—homogenous site location, replication, same seed source, planting timing, and technique—and it remains a good starting point for those embarking on a stocktype study of their own. South and Foster (1993) offer suggestions for heterogeneous sites that include statistical blocking and single tree plots. Recent studies use these suggestions and implement thorough statistical designs for clear results. Haase et al. (2006) address culturing stocktypes in a uniform environment and also use a randomized complete block design with a factorial set of treatments (fertilizer $\times$ stocktype) for their outplanting. Pinto et al. (2011) take it one step further by culturing stocktypes for physiological uniformity and also implementing a randomized complete block design for outplanting. One important tip, touched on by Owston and Stein (1974) but not fully addressed in this article, is making sure seedling planters and handlers do not create confounding. Stocktype planting should not favor one type of stock over another; under no circumstances should a single planter be responsible for planting a single stocktype; either one planter installs the whole trial or several planters equally share the planting of each stocktype. After choosing an appropriate design, using the correct analysis will help get the most out of the collected data. If the trial incorporates a good design, it should be easy to find someone with the knowledge to apply the best analysis; US Forest Service nursery specialists and university faculty are likely candidates to provide assistance with designing and interpreting experiments. Adequately designed experiments and trials will ease statistical analysis, improve interpretation of the data, and add confidence to any recommendations.

Outplanting

When sowing seedlings for a study, it is impossible to predict outplanting conditions and, consequently, the problem with single-year analyses will always be an issue. Regardless of the conditions on the outplanting site, it is paramount to be cognizant of the appropriate planting windows and take advantage of them. Unless it is a part of the study design, it does not help to plant seedlings at the wrong time; the results may not be useful. To bypass single-year analyses, several options exist. The most obvious is to replicate the study

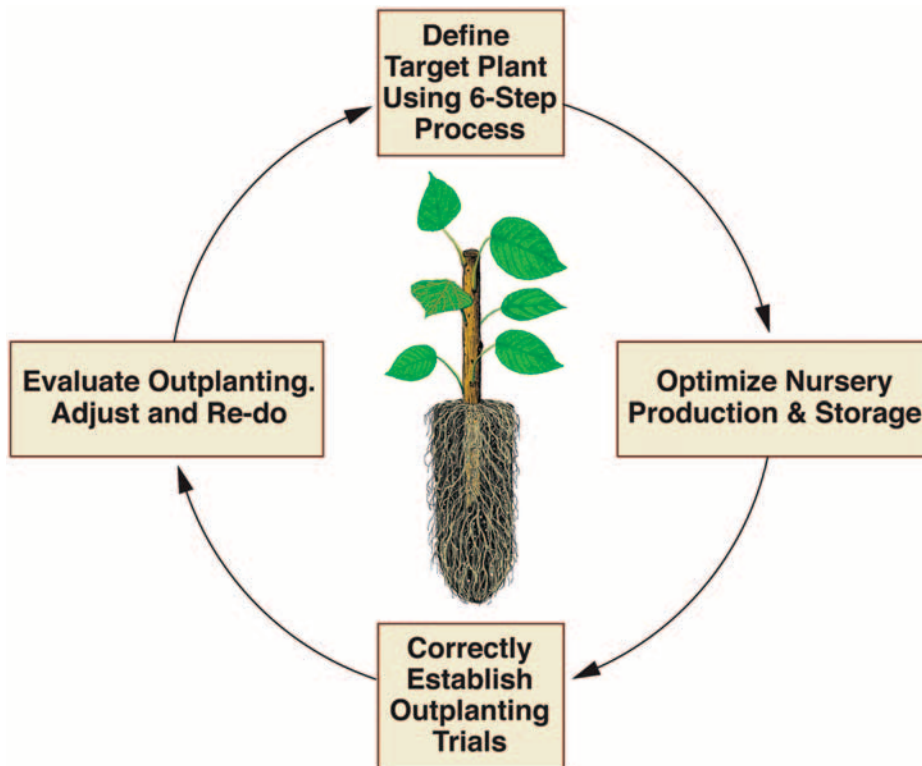


Figure 3. Implementing a stocktype study to determine a target plant should be a circuitous process. Along the way, be sure to start with the TPC, consider the end user, minimize confounding variables, optimize nursery production and storage, correctly establish outplanting trials, evaluate, adjust, and repeat.

several years in a row, hopefully capturing the desired or varied natural outplanting scenarios. However, it is still possible that the chosen years may not be a representative sample of the outplanting conditions hoped for (drought, frost, moist, and hot, to name a few). Another alternative is to create the outplanting conditions you wish to test. In a controlled setting (e.g., an unused nursery bed), one could set up plots to simulate drought, vegetative competition, or mesic conditions (Pinto 2009). With this type of study, it should also be easier to implement robust statistical designs for simpler analysis. Taking the controlled environmental settings one step further, growth chambers are a viable option for testing tougher to control variables such as frost, vapor pressure deficit, light intensity, or even CO₂ levels. Using these last two examples in a stocktype study does remove conclusions from the natural setting, but the degree of control should help to answer specific questions of relative stocktype performance.

Conclusions

New stocktypes are continually entering the market, and some will be better than

others at meeting new management objectives and challenges. Therefore, foresters will also have a need to evaluate stocktypes against the status quo by using stocktype trials. These trials must be done well so that conclusions are sound, biologically and economically. Past stocktype trials often confounded variables, which reduced the ability of the trial to provide quality information about the intrinsic differences among stocktypes—these trials were really evaluating nursery cultural practice. Good stocktype trials require several key components.

First, start with TPC, which serves as a decision guide early in the stocktype selection process; but realize that the concept is the first link in the continuous loop of nursery production, outplanting trials, and evaluation of stocktypes in an ongoing effort to enhance plant quality (Figure 3). Second, pay attention to easily confounded variables: seed source, nonuniform propagation environments, and lack of stocktype-specific cultural practices. Stocktypes are, by definition, inherently different; therefore, confounding can not always be avoided but it should be minimized whenever possible. Third, use a robust study, properly planned, installed, and monitored. If possible, replicate the trial

several years to capture climatic variation, or use controlled environments. The results of any stocktype trial and the relevance of the conclusions garnered are only as good as the effort made in designing the study.

Literature Cited

- AMIDON, T.E., J.P. BARNETT, H.P. GALLAGEHER, AND J.M. MCGILVRAY. 1982. A field test of containerized seedlings under drought conditions. P. 139–144 in *Proc. of the Southern containerized forest tree seedling conf.*, Guldin, R.W., and J.P. Barnett (eds.). US For. Serv. Gen. Tech. Rep. SO-37, South. For. Exp. Stn.
- BURDETT, A.N. 1990. Physiological processes in plantation establishment and the development of specifications for forest planting stock. *Can. J. For. Res.* 20:415–427.
- CHIRINO, E., A. VILAGROSA, E.I. HERNANDEZ, A. MATOS, AND V.R. VALLEJO. 2008. Effects of a deep container on morpho-functional characteristics and root colonization in *Quercus suber* L. seedlings for reforestation in Mediterranean climate. *For. Ecol. Manag.* 256:779–785.
- CREGG, B.M. 1994. Carbon allocation, gas exchange, and needle morphology of *Pinus ponderosa* genotypes known to differ in growth and survival under imposed drought. *Tree Physiol.* 14:883–898.
- DURYEA, M.L. 1984. Nursery cultural practices: Impacts on seedling quality. P. 143–164 in *Forest nursery manual: Production of bareroot seedlings*, Duryea, M.L., and T.D. Landis (eds.). Martinus Nijhoff/Dr W. Junk Publishers, The Hague/Boston/Lancaster, The Netherlands.
- DURYEA, M.L. 1985. Evaluating seedling quality: Importance to reforestation. P. 1–4 in *Evaluating seedling quality: Principles, procedures, and predictive abilities of major tests*, Duryea, M.L. (ed.). Oregon State Univ., Forest Research Laboratory, Corvallis, OR.
- DURYEA, M.L., AND K.M. MCCLAIN. 1984. Altering seedling physiology to improve reforestation success. P. 77–114 in *Seedling physiology and reforestation success*, Duryea, M.L., and G.N. Brown (eds.). Martinus Nijhoff Publishers, Dordrecht, The Netherlands.
- ENDANE, F., AND L.W. CARLSON. 1975. The effect of rooting volume on the early growth of lodgepole pine seedlings. *Can. J. For. Res.* 5:55–60.
- GROSSNICKLE, S.C. 2005. Importance of root growth in overcoming planting stress. *New For.* 30:273–294.
- HAASE, D.L., R. ROSE, AND J. TROBAUGH. 2006. Field performance of three stock sizes of Douglas-fir container seedlings grown with slow-release fertilizer in the nursery growing medium. *New For.* 31:1–24.
- HOBBS, S.D. 1984. The influence of species and stocktype selection on stand establishment: An ecophysiological perspective. P. 179–224 in *Seedling physiology and reforestation success*, Duryea, M.L., and G.N. Brown (eds.). Martinus Nijhoff Publishers, Dordrecht, The Netherlands.

- JACOBS, D.F., K.F. SALIFU, AND J.R. SEIFERT. 2005. Relative contribution of initial root and shoot morphology in predicting field performance of hardwood seedlings. *New For.* 30: 235–251.
- LAMHAMED, M.S., P.Y. BERNIER, AND C. HEBERT. 1996. Effect of shoot size on the gas exchange and growth of containerized *Picea mariana* seedlings under different watering regimes. *New For.* 13:207–221.
- LANDIS, T.D. 2009. The target plant concept. P. 14–31 in *Nursery manual for native plants: A guide for tribal nurseries, Vol. 1, Nursery management*, Dumroese, R.K., T. Luna, and T.D. Landis (eds.). Agric. Handbk. 730, US For. Serv., Washington, DC.
- LANDIS, T.D., R.W. TINUS, S.E. McDONALD, AND J.P. BARNETT. 1989. *Seedling nutrition and irrigation, Vol. 4, The container tree nursery manual*. Agric. Handbk. 674, US For. Serv., Washington, DC, 119 p.
- LANDIS, T.D., AND R.K. DUMROESE. 2006. Applying the target plant concept to nursery stock quality. P. 1–10 in *Proc. of the COFORD conf. on Plant quality: A key to success in forest establishment*, MacLennan, L., and J. Fennessy (eds.). National Council for Forest Research and Development, Dublin, Ireland.
- LANDIS, T.D., R.K. DUMROESE, AND D.L. HAASE. 2010. *Seedling processing, storage, and outplanting, Vol. 7, The container tree nursery manual*. Agric. Handbk. 674, US For. Serv., Washington, DC, 200 p.
- NEWTON, M., E.C. COLE, AND D.E. WHITE. 1993. Tall planting stock for enhanced growth and domination of brush in the Douglas-fir region. *New For.* 7:107–121.
- OVERTON, W.S., AND K.K. CHING. 1978. Analysis of differences in height growth among populations in a nursery selection study of Douglas-fir. *For. Sci.* 24(4):497–509.
- OWSTON, P.W., AND W.I. STEIN. 1974. *A suggested method for comparing containerized and bareroot seedling performance on forest lands*. US For. Serv. Res. Note PNW-222. 12 p.
- PATERSON, J. 1997. Growing environment and container type influence field performance of black spruce container stock. *New For.* 13: 329–339.
- PINTO, J.R. 2005. *Container and physiological status comparisons of Pinus ponderosa seedlings*. MSc thesis, Univ. of Idaho, Moscow, ID. 32 p.
- PINTO, J.R. 2009. *Growth and gas exchange of different ponderosa pine stock types on dry sites*. PhD dissertation, Univ. of Idaho, Moscow, ID, 78 p.
- PINTO, J.R., R.K. DUMROESE, AND J.D. MARSHALL. 2006. Run for cover! What's covering your greenhouse and how is it affecting seedling growth? P. 44–50 in *National Proc. of Forest and Conservation Nursery Associations—2005*, Riley, L.E., R.K. Dumroese, and T.D. Landis (eds.). Proc. RMRS-P43, US For. Serv., Rocky Mtn. Res. Stn., Fort Collins, CO.
- PINTO, J.R., R.A. CHANDLER, AND R.K. DUMROESE. 2008. Growth, nitrogen use efficiency, and leachate comparison of subirrigated and overhead irrigated pale purple coneflower seedlings. *Hortscience* 43:897–901.
- PINTO, J.R., J.D. MARSHALL, R.K. DUMROESE, A.S. DAVIS, AND D.R. COBOS. 2011. Establishment and growth of container seedlings for reforestation: A function of stocktype and edaphic conditions. *For. Ecol. Manag.* 261: 1876–1884. doi:10.1016/j.foreco.2011.02.010.
- PUTTONEN, P. 1989. Criteria for using seedling performance potential tests. *New For.* 3:67–87.
- RIKALA, R., J. HEISKANEN, AND M. LAHTI. 2004. Autumn fertilization in the nursery affects growth of *Picea abies* container seedlings after transplanting. *Scan. J. For. Res.* 19:409–414.
- ROSE, R., W.C. CARLSON, AND P. MORGAN. 1990. The target seedling concept. P. 1–8 in *Proc. of Combined meeting of the Western Forest Nursery Associations*, Rose, R., W.C. Carlson, and T.D. Landis (eds.). US For. Serv. Gen. Tech. Rep. RM-200, Rocky Mtn. For. Range Exp. Stn.
- ROSE, R., D.L. HAASE, F. KROIHER, AND T. SABIN. 1997. Root volume and growth of ponderosa pine and Douglas-fir seedlings: A summary of eight growing seasons. *West. J. Appl. For.* 12(3):69–73.
- ROSE, R., AND D.L. HAASE. 2006. *Guide to reforestation in Oregon*. College of Forestry, Oregon State Univ., Corvallis, OR. 48 p.
- SIMPSON, D.G. 1991. Growing density and container volume affect nursery and field growth of interior spruce seedlings. *North. J. Appl. For.* 8:160–165.
- SIMPSON, D.G. 1994. Nursery growing density and container volume affect nursery and field growth of Douglas-fir and lodgepole pine seedlings. P. 105–115 in *Proc. of Forest and Conservation Nursery Associations*, Landis, T.D., and R.K. Dumroese (eds.). US For. Serv. Gen. Tech. Rep. RM-GTR-257, Rocky Mtn. For. Range Exp. Stn.
- SOUTH, D.B. 2006. Planting longleaf pine at wide spacings. *Native Plants J.* 7:79–88.
- SOUTH, D.B., AND G.S. FOSTER. 1993. An experimental design for outplanting nursery trials on heterogeneous sites. *S. Afr. For. J.* 165:41–45.
- SUTTON, R.F. 1979. Planting stock quality and grading. *For. Ecol. Manag.* 2:123–132.
- THIFFAULT, N., R. JOBIDON, AND A.D. MUNSON. 2003. Performance and physiology of large containerized and bare-root spruce seedlings in relation to scarification and competition in Quebec (Canada). *Ann. For. Sci.* 60:645–655.
- TINUS, R.W., AND P.W. OWSTON. 1984. Physiology research made forestation with container-grown seedlings successful. P. 143–156 in *Seedling physiology and reforestation success*, Duryea, M.L., and G.N. Brown (eds.). Martinus Nijhoff Publishers, Dordrecht, The Netherlands.
- VAN DEN DRIESCHE, R. 1988. Nursery growth of conifer seedlings using fertilizers of different solubilities and application time, and their forest growth. *Can. J. For. Res.* 18:172–180.
- VAN DEN DRIESCHE, R. 1991a. Influence of container nursery regimes on drought resistance of seedlings following planting. I. Survival and growth. *Can. J. For. Res.* 21:555–565.
- VAN DEN DRIESCHE, R. 1991b. Influence of container nursery regimes on drought resistance of seedlings following planting. II. Stomatal conductance, specific leaf area, and root growth capacity. *Can. J. For. Res.* 21:566–572.