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Review

The Scientific Basis of the Target Plant Concept: An Overview

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Abstract: Reforestation and restoration using nursery-produced seedlings is often the most reliable way to ensure successful establishment and rapid growth of native plants. Plant establishment success—that is, the ability for the plant to develop within a set period of time with minimal further interventions needed—depends greatly on decisions made prior to planting, and yet nursery-grown plants are often produced independently of considering the range of stressors encountered after nursery production. The optimal plant or seedling will vary greatly with species and site (depending on edaphic and environmental conditions), and in having the biological capacity to withstand human and wildlife pressures placed upon vegetative communities. However, when nursery production strategies incorporate knowledge of genetic variability, address limiting factors, and include potential mitigating measures, meeting the objectives of the planting project—be it reforestation or restoration—becomes more likely. The Target Plant Concept (TPC) is an effective framework for defining, producing, and handling seedlings and other types of plant material based on specific characteristics suited to a given site. These characteristics are often scientifically derived from testing factors that are linked to outplanting success, such as seedling morphology and physiology, genetic source, and capacity to overcome limiting factors on outplanting sites. This article briefly summarizes the current knowledge drawn from existing literature for each component of the TPC framework, thereby helping land managers and scientists to meet objectives and accelerate reforestation and restoration trajectories.

Keywords: seedlings; plant materials; outplanting; nursery production; genetics; seedling quality

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1. Introduction

This paper is intended to serve as a framework for the Special Issue of Forests (ISSN 1999-4907) *The Scientific Basis of the Target Plant Concept*, building on an emerging body of work that supports the integration of plant biology, environmental conditions, and social factors in the effective use of seedlings for restoration and reforestation. In 1990, the "Target Seedling Symposium" was held in Roseburg, OR, USA, and the subsequent proceedings [1] opened with a preface from Logan A. Norris:

> *Foresters have complained for years about poor seedling survival and growth, often with little understanding of why a specific reforestation effort failed. In some cases, it was stock of inherently low quality due to poor nursery cultural practices, or seedling storage and handling conditions. In other cases, the stock was in top notch shape, but inappropriate for specific site conditions, such as dense competing vegetation, early fall frosts, or high soil temperatures. Sometimes it was all of the above! In trying to solve this problem we too often tried to compartmentalize it and fix each piece... one at a time, often unsuccessfully.*

Following the proceedings of that symposium, nursery specialists developed a new framework designed to quantitatively link seedling attributes with field performance under monitored, replicable conditions. While there are regularly measured and applied parameters, such as seedling height or diameter, the collective knowledge of how seedlings establish, grow, or die should be used to identify those attributes that are most closely linked with outplanting success while fully considering the intended site and associated environmental and social conditions.

As reforestation has evolved from a primarily timber-driven perspective to include a broad range of restoration planting and revegetation activities and objectives, the Target Seedling Concept too has evolved [2]. Various permutations have included direct seeding and the use of cuttings or wildlings in addition to seedlings, resulting in the modification of the name to the Target *Plant* Concept (TPC; e.g., [3]). Over time, different emphasis areas have added or consolidated various tenets of consideration.

Ultimately, the Target Plant Concept is a framework designed to bring plant production and field establishment into a single holistic process. Because many plant attributes can be linked to outplanting success, seedlings in a nursery should be grown with full consideration of the intended outplanting site conditions. Nursery growers and field managers should work in partnership to identify plant attributes that are likely to lead to project success. Dumroese et al. [3] provided a thorough summary of the core tenets and examples of how the framework can be applied.

The global demand for reforestation and restoration seedlings continues to expand through both sustainable forestry and increased attention to degraded lands [4,5]. This increases the need to improve seedling survival rates; therefore, it is critical to maximize the efficiency of nursery production systems, reduce financial and resource waste resulting from establishment failure, and meet the objectives of outplanting projects. Recognizing this demand requires attention to the changing aspects of target plant development, with shifts in objectives and constraints across wide ranges of planting programs. New objectives (e.g., establishing pollinator cover or climate resilience) and challenges (e.g., shifts in precipitation and temperature) drive new research questions. In turn, these questions are met with new and evolving research techniques. The papers contained in this special issue are intended to build on the pioneering work of the 1990 Target Seedling Symposium [1] and highlight the scientific basis that provides the underpinnings of this framework.

2. The Target Plant Concept as a Holistic Framework

The TPC framework brings forward quantifiable plant attributes that are the "targets" for seedling production. The targets can be refined each season based on regular monitoring of field performance. Seedling height and stem diameter are often cited as the most readily measured, and applicable, metrics [6,7]; other attributes, including root systems [8,9] and internal/physiological attributes [10,11], are quantifiable as well and thus worthwhile considerations. As data management becomes more feasible in real-time decision making, application of seedling growth models (e.g., [12]) may enable more robust predictions of post-planting performance.

Applying the TPC approach allows for continuous improvement of nursery production, outplanting, and tending practices. Historically, the TPC had six to eight core components, each of which should be addressed before producing seedlings in a nursery. In the version presented here, we simplify the core to five all-inclusive components (Figure 1). In either case, the TPC can be easily adapted for use with direct seeding, transplanting from other sources, or using cuttings. By discussing each of the five components of the concept (detailed in the following sections) nursery and field partners can work together to define the target plant for each reforestation or restoration project. These five components fall under two overarching goals: first, understanding the environmental, administrative, social, and biophysical conditions around the project scope; and second, deploying mitigating measures that result in lasting positive change in how the project develops over time.

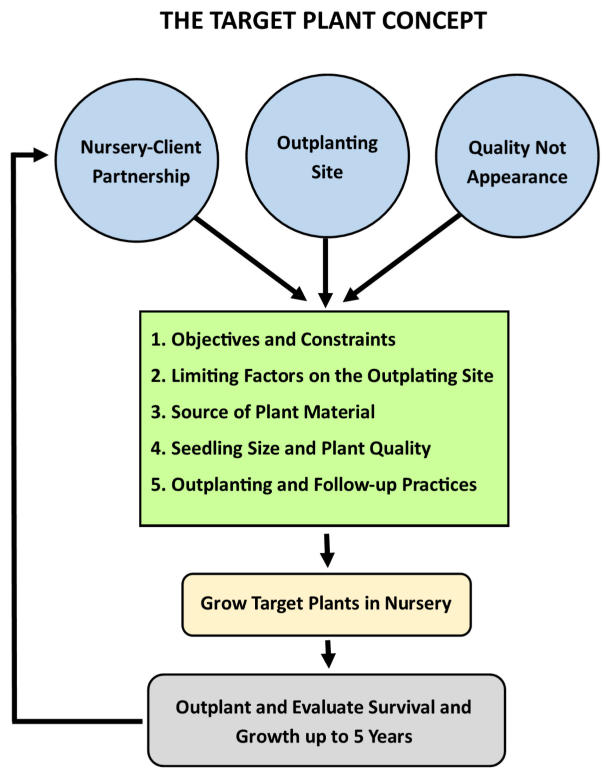

Figure 1. The Target Plant Concept starts with three key elements that guide a cyclic improvement process: nurseries must work together with clients, target plants are defined at the outplanting site, and quality, not appearance, dictates success. Five core components then provide a framework for creating the target plant. The plants are grown, outplanted, and evaluated before starting and improving the cycle again (adapted from Landis [2,3]).

2.1. Identifying Program Objectives and Constraints

Understanding the objective(s) for a given project is critical for guiding the allocation of time, money, and human resources and for defining the target plant. For example, restoring large, degraded areas may require growing small quantities of many species, or large quantities of a few select species. Careful consideration of such a mix should reflect long-term objectives for the planting (e.g., [13]). In one example of defining planting program parameters, a survey of forest sector stakeholders was used to evaluate species preference in Lebanon [14], while another [15] offered a national strategy for federal forests in the USA.

From its basis in reforestation, the concept of understanding the "net present value of silvicultural inputs" requires the project manager to carry all costs forward through rotation length. With this, spending a few cents extra for a larger seedling moves quickly into a meaningful sum of money in forestry operations and must therefore be justified by improvements in growth or survival, which in turn would generate cost savings (e.g., [16]). Similarly, decreasing the number of trees planted per hectare reduces initial tree planting costs (e.g., [17]), which could enable the savings to be invested instead in post-planting treatments or for expanded treatment areas.

Managing genetics toward specific performance attributes has also shifted over time, having gained prominence in forestry programs in many areas, particularly where monoculture plantations are readily employed, (e.g., [18]). Contemporary forestry will likely see an application of genetic resource management to enhance climate resilience [19] in addition to breeding to address evolving pest issues [20]. In essence, these initial costs were justified (i.e., through an initial study) and are "recovered" with harvest and sale in the traditional silvicultural model. Application of the same principles to new objectives, such as plant survival or increased restoration of ecosystem function, will provide alternative strategies for deploying initial investments in outplanting projects.

With the emergence of restoration planting as a significant component of current and degraded forest landscapes globally, the objectives and purposes of using seedlings has shifted. More and more, programs are looking to increase biodiversity, mitigate climate change, and conduct restoration at a large scale. Löf et al. [21] summarized the dialogue addressing this shift and concluded that the need for this restoration is faced with some constraints. Because the focus has shifted towards a restoration base, cost recoveries associated with traditional forestry models are absent; consequently, financial costs for restoration planting are high relative to future direct sources of revenue. As Stanturf et al. [22] pointed out, the more degraded the landscapes are, the more expensive the process is. At the global scale, there is a very large amount of land in need of planting, but there is a shortage of appropriate regeneration material [23]. Finally, for these restoration efforts to succeed, efforts need to provide a positive resource for local and regional communities, effectively recognizing the economic, social, and environmental demands on the landscape. Even with these overarching shifts, the TPC has the flexibility to address each constraint.

Naturally, objectives need thorough planning to be successful. For restoration, this includes choosing appropriate reference sites and choosing plant materials that meet both short- and long-term objectives. In the United States, ecological restorative land management actions aim to produce a “healthy” landscape that provides a range of ecosystem and social services and one that eventually becomes self-sustaining [24]. In this sense, short-term objectives can be the immediate establishment of vegetation structure, soil stabilization, and forage for dependent fauna [16]. Long-term objectives include biotic diversification, improved hydraulic cycling, and increased resilience to future environmental degradation and climate change. A key tenet to meeting these goals is managing the appropriate genetic resources (discussed in Section 2.3; [25]). While silvicultural programs might have well-developed genetic plans, native plant systems are still “works in progress” and in need of much research.

As an example of how the TPC has evolved and enabled shifts in defining outplanting success, it is now more common for restoration and reforestation projects to effectively and appropriately incorporate recognition of cultural values and resources in planning, monitoring, and evaluation. The use of traditional knowledge to define these objectives is important [26]. Inherently, the TPC’s holistic nature offers flexibility in its inputs and implementation. It can accommodate diverse projects, work across varying scales, and support different stakeholders. Acknowledging there is no “one size fits all” approach, the TPC produces a space for creativity, adaptability, expansion, and inclusion. This works particularly well when objectives are considerate of the fact that Indigenous cultures have been managing ecosystems for millennia. The extensive knowledge behind this management history has been shown to complement restoration objectives as well as enhance the science [27,28]. The same is possible in creating target plant materials. Traditional knowledge can guide and inform site preparation techniques including burning [29,30], genetic selection of desired plants and plant characteristics (e.g., textiles, food, and medicine), target plant size (e.g., recognition that, for example, in post-harvest reforestation activities seedlings may be selected with an aim towards optimizing economic performance or maximizing productivity, while in restoration projects seedlings may be pointed towards objectives around achieving a higher level of ecosystem function), and can provide information on planting sites including potential site limitations (e.g., seasonal changes or weather patterns). The incorporation of traditional knowledge also empowers communities associated with the project, giving value beyond those just associated with costs.

Rarely is a project fully funded, regardless of the industrial or ecological purpose. Financial capacity is often a constraint and in a holistic approach such as the Target Plant Concept, such constraints should be identified as early and fully as possible. For example, seedling production depends on a mix of human and natural resources as well as physical infrastructure. While post-harvest reforestation systems that employ technologically advanced producers of nursery stock may be well developed in some countries [31,32], the absence of advanced technologies in other countries [33] can lead to a lack of seedling production capacity despite critical ecological need [34].

Each production goal requires different infrastructure needs such as containers, growing medium, and irrigation systems, as well as knowledge of plant growth and development for the selected species. The more clearly defined objectives are, the more likely it is that the program will be properly resourced and managed. Similarly, it is important to identify potential constraints, such as access to funding, water, labor, or other resources. Once constraints are identified, partners can determine how they can be mitigated through effective planning.

Changing environmental conditions and increasingly unique planting scenarios also help shape objectives and constraints. For example, dryland systems occupy nearly half the world's terrestrial surface, and an estimated one-third to one-half of this area needs restoration [35,36]. These systems are particularly unique and challenging because natural recruitment is temporally and spatially irregular, so trying to restore using human-based timelines, such as those driven by grant cycles and program lengths, and spatial patterns, such as across different ownerships, is very difficult; see [37]. Add social challenges, from economic returns to conservation values, and the equation becomes more complex. All these factors contribute to how a project is initiated and can generate new research questions.

2.2. Limiting Factors on the Outplanting Site

Every outplanting site is different and should be characterized before nursery production begins. Many factors can limit plant survival, growth, and reproduction on the planting site, and those issues can often be identified long before planting. Effective identification of those factors can lead to implementation of scientifically justified mitigating measures. Common issues are the depth and type of soil; the timing, amount, and form of precipitation; site accessibility and current uses; the type and level of vegetative competition and animal browse likely to occur; and exposure to pests and pathogens.

There are often multiple limiting factors at a site, and their effects may be sequential and cumulative. In most cases, all factors cannot be mitigated, so it is important to recognize and address the ones that are most problematic. Factors that limit seedling establishment are often classified into either atmospheric or edaphic environments, and some, such as wildfire, can span both. Light, temperature [38], pathogenic fungi, insect pests, competing vegetation [39], and animals [40] are some of the most common limiting factors above ground. Conversely, in addition to soil compaction, composition, and structure, common below ground factors can include water [41], mineral nutrients [42], pathogenic fungi [43], insect pests [44], temperature [45], and mycorrhizal fungi [46]. The eccentricities of many of these variables are complex and often vary both spatially and temporally, thus the need for scientific study. Knowing how these factors interact in detail can help shape the desirable attributes of a target plant.

Nurseries have the capacity to grow seedlings of a variety of shapes and sizes within a single- or across multiple growing seasons (see Section 2.4). With this capacity came the idea of growing seedlings with specific phenotypes to help overcome limiting factors. That is, manipulating morphological traits such as root length or height to address site factors such as soil depth or water availability [11,39,47]. This becomes another reason to expand the scientific basis of matching target morphologies with specific site limitations. In addition to manipulating seedling shape and size, site preparation techniques can also be used to mitigate limiting factors on the outplanting site (see Section 2.5).

2.3. Managing Genetic Resources

Selecting a particular species or multiple species for a project will depend on the availability of propagation material, project goals, site conditions, and limiting factors. A diverse mix of native species is usually best for projects that aim to restore the natural structure and support the ecological function of habitats. Once the species of interest have been identified, sources of seeds or cuttings for propagation in the nursery must be identified.

A considerable body of research has led to the delineation/development of seed zones based on local adaptation for several timber species, and as the science has advanced, the precision and accuracy of these seed zones has increased [48]. When it comes to native plant populations, sourcing protocols are less developed for individual species; however, knowledge and science are also continually improving [49–51]. In the interim, some general guidelines for selecting appropriate native seed sources are based on climate data [52], and some have the capacity to model future climate scenarios [53]. Another tool combines genecological and future climate models for specific species [54]. Still others use a stepwise process that emphasizes how each level of decision making can be managed to ensure local adaptation and genetic diversity [55]. In this practice, sources should be selected from nearby populations occupying environments similar to the planting sites and should be collected from many different individuals to allow for genetic diversity that supports resiliency [55].

Depending on the objectives of the project and the quality and quantity of local seed sources, it may be necessary to collect seed from non-local sources, or even use cultivars, to ensure access to high quality, viable, and genetically diverse seed [56–58]. This will maximize the adaptive potential of the planted population to current and future conditions. Some species are highly sensitive to differences in elevation, moisture gradients, or temperature and may not grow well if planted in conditions different from those in which they evolved; others are more general in their habitat needs. Thus, if appropriate seeds or cuttings are not available, a different species may be better for meeting the project's long-term objectives.

When collecting seeds and cuttings, care must be taken to avoid overharvesting a given population. While traditional reforestation approaches used a mix of wild and orchard produced seed, restoration plantings typically rely exclusively on the former. A growing body of literature helps to articulate the risks of overharvesting plant propagules (e.g., [59,60]). A clear understanding of the impacts of harvesting on plant populations among those involved in seed procurement, as well as the development of more robust systems of seed production (e.g., [60–62]), will ensure that target plants are grown with ethically sound protocols regarding the sourcing of genetic material.

Contemporary and progressive projects aimed at enhancing resilience of ecosystems to climate change will integrate broadly with genetic management objectives. While major demands for seedlings for large-scale tree planting campaigns (e.g., [4]) may well result in use of non-native species, this pathway should be considered carefully for potential future implications. Looking at interspecific and intraspecific approaches to assisted migration (e.g., [63]), there are emerging pathways that will increase confidence in the ecological suitability of such approaches. Alternatively, breeding programs may increasingly focus on developing trees resistant to specific pests or pathogens [20,51,64,65], seek to promote drought tolerance [66], or enhance other attributes related to plant establishment in novel ecosystem conditions. Ultimately, society must openly approach the benefits and risks associated with genetic modification of tree species in looking at the holistic picture of carbon benefits, plant health, economic considerations, and conservation and ecosystem function [67].

2.4. Seedling Size and Quality

There are hundreds of ways that plants can be grown in a nursery, using different container sizes, fertilizers, irrigation schedules, and countless other tools. The result is seedlings that come in an array of different shapes, sizes, and ages. The referential term "stocktype" was developed to describe "how" a seedling is produced and thus conjure up a visual idea of what a seedling should look like. Therefore, "stocktype" inexactly describes the specific nursery cultural methods used to influence plant growth and development to achieve targets.

The first stocktype decision is whether to grow bareroot or container plants. Containers are available in an assortment of shapes, sizes, volumes, materials, and densities allowing a grower to customize the way a seedling is grown for the intended outplanting site (and its limiting factors), while also considering the growth rate of the species. Container selection will impact seedling development in the nursery and potentially in the field (e.g., [33,68,69]). Similarly, bareroot seedlings can be grown to different sizes through a variety of strategies such as seedbed density, growing for multiple years, or by starting with plug transplants. Because there are so many choices, stocktype studies have always been a topic of interest. Knowing which stocktypes offer advantages for different outplanting conditions can mean the difference between establishment success or failure, or the difference in reaching free-to-grow (i.e., the point at which the plant can continue its growth unimpeded by normal limiting factors) status quicker. The scientific literature offers plenty of examples of stocktype studies. It is important, however, to carefully examine their methodologies as it is easy to confound study designs and misinterpret results [70].

The phenotypic variation achieved through the manipulation of stocktype has been linked to overcoming several limiting factors. For example, seedlings with larger or longer root systems may have better survival and growth on droughty sites [39,47,71,72]. Seedlings faced with potential competition do better when they are larger in size so they can compete for light [73–75]. Starting with larger seedlings has also shown to be beneficial as they maintain their size advantage over smaller stock through time [76–79]. These are just a few of the modifications that can be done culturally to facilitate adaptation for improved post-outplanting performance. Though there are many different stocktypes, with many different purposes, ultimately, their performance is highly reliant on seedling quality.

Plant quality is defined by physical and physiological attributes that allow a plant to survive and grow once outplanted. This too has been the topic of many studies, spanning basic science and knowledge discovery to application in the nursery and post-outplanting [80]. The cultural inputs of the nursery are what dictate seedling quality. Irrigation and fertilizer regimes are used to maintain plant moisture and nutrient levels to support growth and survival after planting [10,81]. Appropriate temperature and light regimes must be timed correctly so they align with important phenological stages of development [82]. It is the critical balance of how these factors interact that lend toward high quality seedlings, and when seedlings experience unusual, unintended, or harsh stresses in the nursery, plant quality diminishes and can result in other problems such as outbreaks of harmful insects and disease. It should also be noted that serious reductions in plant quality can happen outside the nursery environment, e.g., while seedlings are being stored or held over, during transport to the planting site, or mishandling during planting.

With the TPC as the guiding framework for quantifying the attributes that define seedling quality, nursery growers, silviculturists, and other practitioners who connect the field and nursery components of planting projects benefit from communicating clearly and making data-driven decisions. Effective evaluation of attributes such as root growth potential (e.g., [83]) can inform outplanting performance under a range of conditions and thus increase capacity for outplanting success [84]. During nursery production, seed and germination management (e.g., [85]), fertilization (e.g., [68]), growing media composition (e.g., [33,86,87]), lighting (e.g., [88]), and irrigation and hardening regimes (e.g., [89]) each represent inputs that can be adjusted to align the plant produced in the nursery with the elements that may enhance success after planting.

2.5. Post-Nursery Practices

Once seedlings are removed from the nursery, they immediately become susceptible to stresses associated with handling, storage, transportation, planting, and environmental conditions [90]. Careful handling during these periods ensures seedling quality is preserved as best as possible and maintained until the optimal planting window is reached. Some work has shown that rough handling of seedlings (e.g., dropping packed boxes of seedlings) has consequences for growth and survival [91]. Much work has also been done looking at optimizing cooler or freezer storage to synchronize with seedling dormancy, stress resistance, and timing to bud break (see [92]). All these post-nursery practices are important lead-ins to critical components of outplanting timing and method.

The timing and method of outplanting should be considered before the crop is even sown in the nursery. The outplanting window should coincide with both the physiological readiness (dormancy status and stress resistance) of the seedling and favorable environmental conditions for plant growth and survival, which are typically seasons that offer adequate soil moisture and favorable root and shoot temperatures (covered in 2.2 Limiting factors on the outplanting site). Working backward from this window of time will help growers schedule the entire production cycle, from seed collection, through sowing and growing, to hardening [93]. A typical planting season in the United States might extend from late winter to early spring, but in some instances (e.g., high elevation, heavy rains, or drought conditions), considerations should be made to shift the planting to mid-summer or fall [94–96].

Once seedlings arrive on an outplanting site, there are several tactics that aid establishment success. Field practices can range in intensity from simply planting into relatively undisturbed soils to complex and interactive mechanisms that require breaking up compacted layers, reducing onsite vegetation, or coordinating protection against a potential wide array of damaging elements. Before seedlings are outplanted—and potentially through follow up treatments—addressing current and potential future vegetation on the site is important. Given that outplanted seedlings will compete for water, light, and nutrients with existing and emerging plants, identifying if mitigating measures such as herbicide application (e.g., [97]), mechanical treatments (e.g., [98]), or suppressive mulches (e.g., [99]) are effective at ameliorating the effects of the limiting factors can have an important impact on seedling establishment success.

Selecting the appropriate tool for planting is important. Whether hand-operated or mechanized, the chosen planting tool should make the right size hole for the seedling's root system [100] to optimize root–soil contact after planting [80] and to avoid factors detrimental to root egress such as compaction (e.g., [101]).

Fostering growth after planting presents another suite of tools to support outplanting performance. Research has shown that seedlings subjected to protective treatments such as tubes or shelters often fare better against animal damage [40,102–104]. Protective structures may also create microenvironments that improve seedling performance [105–107], but in some cases may instead create unsuitable microclimates [108]. Less common practices in field establishment can include using physical devices to moderate against sun [109] or frost [110] damage, the effects of which can be mitigated through interrupting solar radiation patterns. Additive benefits of pairing cultural practices (e.g., [111]) that enhance cold tolerance with physical treatments could lead to further gains in outplanting success.

Watering seedlings before and after planting (either manually or through rainfall) contributes to higher survival and growth [99,112,113]. Field fertilization can enhance seedling growth on nutrient-poor sites [114,115] and can be tailored to the specific limitations of a given site or in response to plant needs.

3. Conclusions and Future Directions

The true test of target plant success is field performance. Plants and projects should be regularly monitored and evaluated after outplanting to assess survival and growth and revisit performance compared to initial objectives and those practices that were employed. This information helps to set and refine targets for future crops and to connect the nursery production and field performance phases of projects in a quantifiable manner; effective communication of the knowledge gained from these monitoring and evaluation programs must be communicated across project funders and organizers, seedling growers, outplanting professionals, and project managers to enable the largest gains in achieving program objectives. Through this approach, the target plant concept becomes applied as a living driver of best practices. This process also offers the opportunity for scientific inquiry. Rigorous application of the scientific method allows us to understand the mechanisms that contribute toward meaningful results. It also allows for science-based decision making among land and nursery managers.

The importance of seedlings as a part of addressing global plant material needs or restoration and reforestation is rapidly evolving from being timber oriented, to inclusive of broader habitat restoration objectives, to now an exploration of how these practices can be used to expand terrestrial carbon storage. With more than 220 billion seedlings needed for these collective purposes [4], outplanting survival presents itself as one of the most critical opportunities to expand the impact of tree planting. Our need for targeted, science-based practices to improve these efforts will continually evolve to meet those needs.

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