

International practices for regenerating and restoring forest trees by seeding – an introduction

Emile S Gardiner¹✉, John A Stanturf²

¹USDA Forest Service, Southern Research Station, Center for Bottomland Hardwoods Research, Stoneville, MS, USA

²Institute of Forestry and Rural Engineering, Estonian University of Life Sciences, Tartu, Estonia and InNovaSilva, Vejle, Denmark

✉ emile.gardiner@usda.gov

ARTICLE INFO

Citation:

Gardiner E, Stanturf J (2026) International practices for regenerating and restoring forest trees by seeding – an introduction. *Reforesta* 21:1-9
DOI: <https://dx.doi.org/10.21750/REFOR.21.01.131>

Editor: Vladan Ivetić

Received: 15.11.2025

Accepted: 15.12.2025

Published: 20.01.2026



Note

This paper is a part of a Special issue on International Practices for Regenerating and Restoring Forest Trees by Seeding, edited by Emile S Gardiner and John A Stanturf

Copyright: © 2026 Gardiner Emile S, Stanturf John A. This work is licensed under a [Creative Commons Attribution 4.0 International Public License](https://creativecommons.org/licenses/by/4.0/).



Abstract

This manuscript introduces the current special journal issue *International Practices for Regenerating and Restoring Forest Trees by Seeding*, for which the concept and effort to undertake were motivated within the IUFRO Task Force on Transforming Forest Landscapes for Future Climates and Human Well-Being. The journal issue, comprised of contributions from North America, South America, Europe, Asia, and Oceania, represents a significant range of seeding activities inclusive of scores of species, forests, forestation sites, and climates. Approached as an information guide and source of advancements that are being studied and applied in contemporary practice around much of the globe, *International Practices for Regenerating and Restoring Forest Trees by Seeding* provides a synthesis of regional practice and research intended for an audience of early career scientists, practitioners, and policy makers working in forest restoration.

Keywords

forest restoration, forestation, forest degradation, direct seeding, artificial regeneration

Introduction to international practices for regenerating and restoring forest trees by seeding

Forestation is the process of establishing trees to create forest cover. Generally encompassing afforestation, reforestation, and forest restoration, forestation is accomplished through artificial regeneration practices or through practices that promote natural regeneration. However, the term has been most associated with approaches to create forest cover that involve artificial regeneration. Seeding, in the context of forestation, is a means of artificial regeneration in which plant seeds are distributed to propagate desired forest vegetation, particularly trees and shrubs (Deal 2018). While only two broad methods of seeding are recognized, broadcast and direct seeding (Table 1), a diversity of seeding approaches have been developed to initiate regeneration of sites where the natural regeneration process of desired species has been degraded such that it is limited or unlikely to occur. The promotion of naturally developing seedlings and forest structure, a broad applicability at all spatial scales, a relatively low cost, a high feasibility for regenerating remote sites, and a low operational

intensity are among the favorable characteristics that coalesce to promote seeding as a promising means of artificial regeneration (Löf et al. 2019). Thus, there is currently marked potential for seeding to be a viable option for artificial regeneration within the global area of deforested and degraded forest landscapes.

Forest workers began adopting the use of seeding to regenerate deforested or degraded woodlands and forests several centuries ago. One of the earliest documented efforts to establish forests through seeding originated from Europe during the early 14th century and rudimentary systems to support seeding efforts appeared as early as the 15th century, much earlier than systems for planting seedlings (Harmer and Kerr 1995; Huth et al. 2017). In the ensuing centuries, the European population and its exploitation of forest resources grew rapidly—this prompted early policy aimed at mitigating forest loss that encouraged forest regeneration and more extensive use of seeding (Huth et al. 2017). During the 17th century, heightened forest exploitation and expansion of agriculture in Europe precipitated the concept of forest sustainability and initiated modern forestry (Huth et al. 2017). As the primary means of artificially establishing forest stands, seeding was foundational to the silvicultural systems being developed and applied to temper the forest exploitation sweeping through much of Europe (Huth et al. 2017). Seeding remained the primary means of artificial regeneration throughout much of Europe until the early 20th century when development of operational forestry led to advancement of regeneration methods based on planting seedlings (Huth et al. 2017; Löf et al. 2019; but see Harmer and Kerr (1995) regarding 17th century Great Britain).

Seeding eventually spread to other regions of the globe, for example, appearing in North America during the early 20th century (Toumey 1916). In most instances, it was introduced by practitioners faced with tremendous forest regeneration needs. In other words, practitioners were motivated by the search for a low-cost approach to artificial regeneration that could be adapted for the species and forests of interest and scaled for application to relatively large areas. In the case of North America, a wave of massive deforestation, e.g., millions of ha in the southern USA alone, was experienced across several regions of the continent when industrial lumbering swept across certain forested regions in the late 19th and early 20th centuries (Barnett 2014). Supported by comprehensive research to address the issue, operationally scaled successes with seeding conifers were realized in multiple regions of North America during the mid-20th century, e.g., pine (*Pinus* spp. L.) species in the southern region of the United States (1940s), Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) and other conifers in the Pacific Northwest region of the United States (1940s), and jack pine (*Pinus banksiana* Lamb.) in Ontario, Canada (1950s) (Scott 1970; Barnett 2014; Downer et al. 2024). Thus, seeding has historically been integral to large-scale forestation, persisting through time and across continents with the rise of modern forestry practices.

Contrary to the history of successes, forest establishment by means of seeding began to fall out of favor in many regions by the early 20th century. This can be attributed to multiple reasons including innovations that drove high success with planting seedlings in industrial reforestation operations. Additionally, contemporary application of seeding is often limited by biological, ecological, or practical constraints. These constraints, along with advancements in nursery culture, genetic improvement of nursery stock, and forestation practices, have solidified planting seedlings as the primary means of artificial regeneration in most operational settings. Though seeding usually demonstrates an initial cost advantage over planting seedlings, the more intensive and costly planting will usually demonstrate higher establishment success and

Table 1. Glossary of seeding terms¹.

Term	Definition
Seeding	The distribution of seed by hand, machine, or aerially in artificial regeneration (Deal 2018). Two methods of seeding are recognized, 1) broadcast seeding and 2) direct seeding . Sowing is synonymous with seeding.
Broadcast seeding	A method of seeding in which seeds are spread throughout an area onto the ground without incorporation into soil. Broadcast seeding can be accomplished through 1) Hand seeding , 2) Machine seeding , or 3) Aerial seeding . To broadcast seed by hand, workers walk systematically through the regeneration area casting seed with their hands or with a hand-held seed spreader. Broadcast seeding with a machine involves the use of a vehicle-drawn seeding implement or seed spreader. The type of vehicle used in the operation, e.g., draught animal, tractor, truck, off-road vehicle, or all-terrain vehicle, is determined by the size of the seeding area, the size of the seeding implement, and the terrain of the seeding area. Aerial seeding is accomplished with either crewed (e.g., helicopter) or uncrewed (e.g., aerial drone) vehicles equipped to carry and spread seed. Seed to be broadcasted is often mixed with an inert matrix (e.g., sand) or pelleted to improve flow through the seeding machine, trajectory of fall through the air, distribution on the ground, contact with soil, or probability of germination.
Direct seeding	A method of seeding that involves sowing seed into furrows or holes in soil, i.e., analogous to “planting” a seed. The furrows or holes are established to control the location and spacing of seed and subsequent seedlings on the regeneration site. Direct seeding can be accomplished through 1) Hand Seeding or 2) Machine seeding . To direct seed by hand, workers walk systematically through the regeneration area, create a small furrow or hole with a hand tool at the sowing spot , deposit seed in the furrow or hole, and cover the seed with soil dug to create the furrow or hole. Machine seeding involves the use of a seeding implement or planting drill drawn by a draught animal, tractor, truck, off-road vehicle, or all-terrain vehicle. Planting drills and seeding implements used for direct seeding are designed with coulters to create the furrows where seed is deposited and discs or packing wheels to cover the seed with soil and close the furrow. Advancements in development of terrestrial drones and aerial drones for direct seeding show promise for their use in the near future. Drilling is synonymous with direct seeding.
Drone seeding	Seeding, either broadcast or direct, accomplished with a drone . A drone is an uncrewed vehicle, either aerial or terrestrial, used to distribute seed. Terrestrial drones designed for seeding are typically autonomous planting machines for seed.
Line seeding	A variant of direct seeding in which seed is sown in linear furrows established across the forestation area.
Hydroseeding	A variant of broadcast seeding in which seed is mixed into a slurry of mulch and water then sprayed onto the regeneration site with hydraulic equipment.
Pneumatic seeding	A variant of broadcast seeding in which seed is blown onto the regeneration site with pneumatic equipment.
Precision seeding	Using GIS, sensors (e.g., LiDAR), and variable-rate technology to map microsites and plan and deliver seeding. Seeds are precisely placed at optimal depth and spacing or location, based on pre-sowing site maps. Precision seeding is especially useful for establishing mixtures and for seeding desirable microsites known to favor germination and seeding establishment.
Seed pelleting	Pelleting coats seeds with inert materials to render them uniform in size, shape, and weight, or to increase probability of germination. This process is especially useful for small or irregularly shaped seeds. Seeds are pelleted with coating materials (e.g., clay or seed treatments such as stimulants or protectants). Seed encapsulation or coating are synonymous with pelleting.
Seeding hole	A relatively large and deep hole that is dug for direct seeding on steep terrain or on highly erodible soils. Soil removed from the hole is often mixed with organic matter or fertilizers to prepare the seedbed and improve seedling rooting and growth.
Sowing spot	The precise location on a forestation site where a seed or seeds are sown when direct seeding.
Spot seeding	Sowing several seeds per sowing spot. Either broadcast seeding or direct seeding can be used for spot seeding.

¹ Growth and development of seeding efforts across the many forested regions of the world have introduced inconsistencies in terminology usage to the literature. Considering the range of manuscripts compiled and the intended user, the value of this journal issue as a resource to the practitioner and student hinges on consistent use of clearly defined terms. Table 1 presents a glossary that should clarify usage, reduce ambiguities, and enable the reader to appreciate relationships between terms applied throughout the issue.

rate of stand development (Grossnickle and Ivetić 2017). This is notably the case for species with seed traits that render them problematic for seeding, such as some light-seeded species and those with seed that show dormancy, sensitivity to desiccation, poor storage, or high susceptibility to depredation (Figure 1). Poor establishment success and relatively slow stand development also materialize when seeding high productivity sites with unchecked growth of competing vegetation. Indeed, issues like seed depredation and competing vegetation led 17th century English practitioners to concentrate seeding in small “garden” areas adjacent to the regeneration site where the effort could be protected and tended to produce seedlings for transplanting (Harmer and Kerr 1995). While early and present-day research advances have addressed some of the issues mentioned above, particularly for a locale or a region, many remain easier to overcome in a seedling nursery setting rather than a field setting.



Figure 1. A pedunculate oak seedling (*Quercus robur* L.) emerging from a prototype “seed tube” designed to protect seed from depredation and provide a favorable microenvironment to the germinant. (Photo credit: Magnus Löf).

Still, seeding has remained integral to contemporary forest regeneration prescriptions for some regions, forest types, site conditions, and forest management regimes (e.g., see Ivetić and Marinković (2026) in this issue for oak (*Quercus robur* L.) stand establishment in Serbia) and is regaining favor in forest restoration settings (e.g., large scale, remote sites where planting seedlings is not practical, where planting

seedlings may be restricted by access or cost, where seeded species are used as framework species, or to enrich plantings for developing complex forest structure). In these settings, contemporary demands for seeding are pushing innovation to improve success, many of which are addressed in this journal issue.

Advances in research and application of seeding are improving today's forestation efforts by addressing a varied list of issues and inefficiencies encountered during operational seeding (Stanturf et al. 2024). New and improved seed delivery technologies represent an important source of advancements (Figure 2). For example, developments in aerial drone and drone-based sensor technologies have redefined how broadcast seeding is conducted in many regions while terrestrial and aerial drone-based platforms show promise for expanding precision seeding to favored microsites on large and remote forestation areas (Downer 2024; and see Castro et al. (2026) for seeding Mediterranean pines and Wang et al. (2026) for seeding *Pinus massoniana* Lamb. in China published in this issue). Too, engineering improvements to machine seeders are providing efficient and effective means to sow seed mixtures, e.g., mixtures of differently sized seeds for seeding former agricultural sites in New Zealand (see Lord and Moss-Mason (2026) in this issue for seeding in temperate New Zealand).

Fresh approaches to sourcing and harvesting seed also contribute to the recent advances that are improving seeding. In this respect, drone technologies are demonstrating utility for identifying source trees and monitoring fruit ripeness, and technological development is advancing towards seed harvesting capabilities which could be particularly useful in tropical regions where source trees can be widely dispersed and difficult to access (Stanturf et al. 2024). Better knowledge and protocols to ensure appropriate genetic sourcing for disease resistance, site suitability, climate adaptation, or other issues (see Pansing and Tomback (2026) for seeding whitebark pine (*Pinus albicaulis* Engelm.) and Lord and Moss-Mason (2026) for temperate New Zealand in this issue), along with seed networks for inventorying and distributing seeds, such as those established in Brazil (see Engel et al. (2026) for seeding in Brazil in this issue), are safeguarding future forest health and ecological success along with addressing operational demands for seeding.

Further, advances that lessen barriers to establishment success and development of desired forest cover have been realized through novel technologies and approaches that protect seed, facilitate seedling establishment, and prepare and manage the forestation area. Refined seed technologies, such as coating or encapsulating seed in briquettes or balls that can improve seed distribution, reduce seed desiccation, reduce seed predation, and facilitate seedling growth, are supporting seed conservation by benefiting seedling establishment (see López-Barrera and Garcia-Hernández 2026) for seeding oaks (*Quercus* spp. L.) in Mexico, Sudrajat et al. (2026) for seeding in Indonesia, and Castro et al. (2026) for seeding Mediterranean pines in this issue). Seed supply limitations in some regions have also driven the development of more efficient strategies for sowing seeds, e.g., precision seeding of microsites known to have higher probabilities of establishment success (see Pansing and Tomback (2026) for seeding whitebark pine and Castro et al. (2026) for seeding Mediterranean pines in this issue). More thoughtful plantation design and application of improved site preparation and management practices that control invasive species, mitigate degraded soil and hydraulic functions, or minimize animal damage have increased successes in promoting development of desired forest cover and achieving improved ecological functions (see Engel et al. (2026) for seeding in Brazil, Gardiner and Stanturf (2026) for

seeding bottomland oaks, and L f et al. (2026) for seeding oak in southern Sweden in this issue) (Figure 3). Thus, recent progress in research and application has fostered the opportunity for greater use of seeding in forestation by improving establishment success on forestation sites, raising cost effectiveness of seeding operations, and ultimately improving ecological and economic sustainability on degraded and deforested sites.

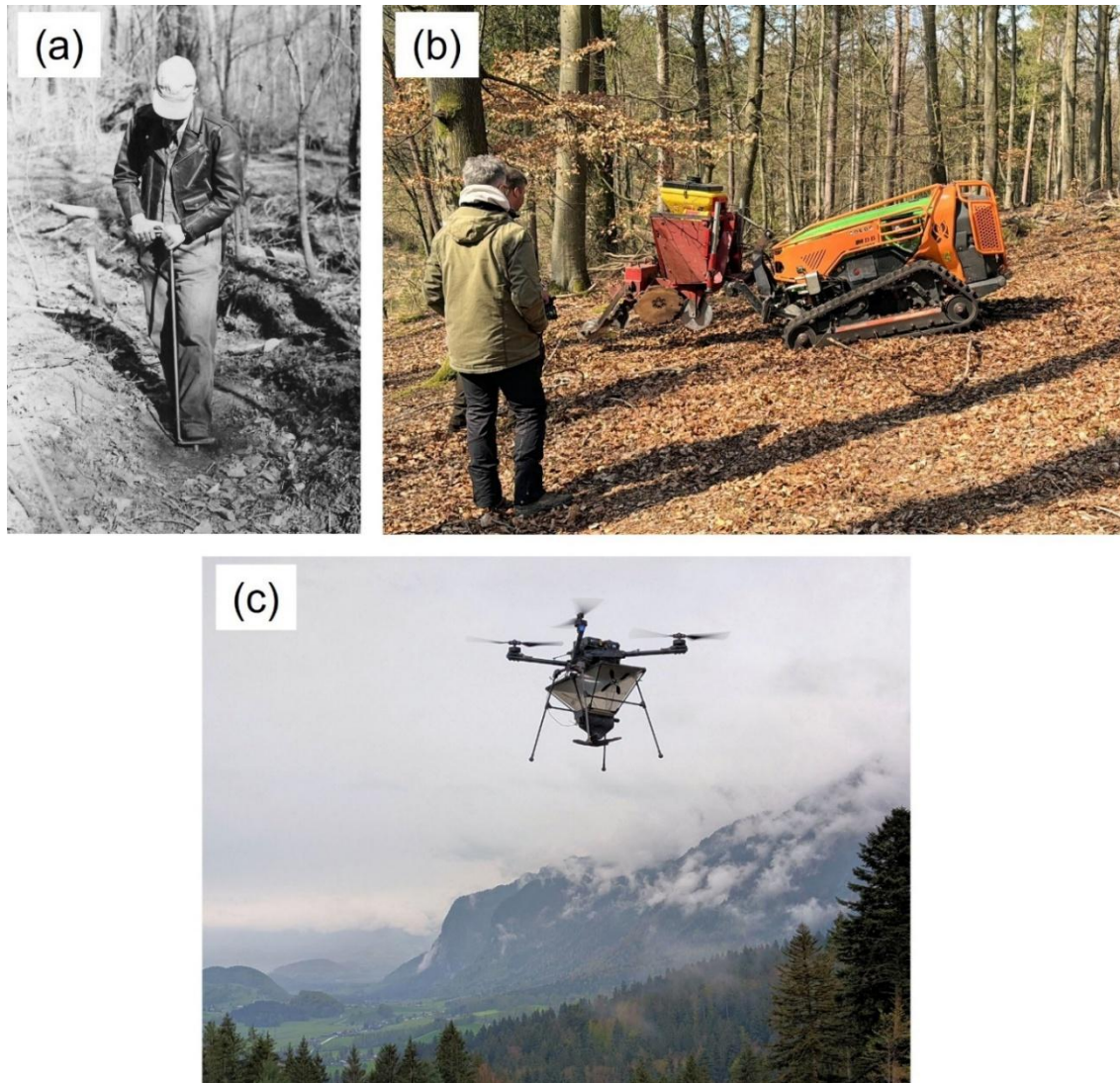


Figure 2. Advancement of seed delivery technologies: (a) a seeding tool used in the 1950s to create a small dimple in the soil surface for direct seeding bottomland oak (*Quercus* spp. L.) acorns, (b) a remotely controlled terrestrial rover used for direct seeding in degraded forest stands, (c) an aerial drone capable of broadcasting seed over relatively large and inaccessible sites. (Photo credits: (a) US Forest Service, Center for Bottomland Hardwoods Research, (b) Skyseed GmbH, Germany, (c) Skyseed GmbH, Germany).

The concept and effort to undertake this special journal issue was motivated within the IUFRO Task Force on Transforming Forest Landscapes for Future Climates and Human Well-Being. The intention was to produce a supplement to *Implementing Forest Landscape Restoration, A Practitioner's Guide*, which was published by IUFRO in 2017

(Stanturf et al. 2017). We approached this supplement as an information guide and source of advancements that are being studied and applied in contemporary practice around much of the globe. In this context, this issue on *International Practices for Regenerating and Restoring Forest Trees by Seeding* is intended to provide a synthesis of regional practice and research for an audience of early career scientists, practitioners, and policy makers working in forest restoration. Some contributed manuscripts are scoped by region or forest type, while others are species centric. Accordingly, manuscripts vary in length and detail, ranging from comprehensive syntheses to short case studies, depending on the level of development and use of seeding practices within the region or for the species of interest. Certainly, this journal issue is not inclusive of all seeding practices, either operational or experimental, being conducted across forest landscapes worldwide. Too, it was not our objective to discern the merits of seeding relative to the other means of active artificial forest regeneration, i.e., planting seedlings—others have begun laying the foundation to comprehensively approach this question (Lázaro-González et al. 2023). However, with contributions from North America, South America, Europe, Asia, and Oceania, it does represent a significant range of seeding activities inclusive of scores of species, forests, forestation sites, and climates. Thus, the substantial seeding expertise, knowledge, and practical experience captured in *International Practices for Regenerating and Restoring Forest Trees by Seeding* will provide the forest restoration community with a key resource for advancing global forest restoration.



Figure 3. European beech (*Fagus sylvatica* L.) seeded beneath a poplar (*Populus* spp. L.) plantation established on former agricultural land. This practice can be used to enrich fast-growing plantations with desired slower-growing species and increase forest structure complexity in forest restoration settings. (Photo credit: Palle Madsen).

Acknowledgement

The article is an activity within the work of IUFRO Task Force “Transforming Forest Landscapes for Future Climates and Human Well-Being.”

Disclaimer

The use of trade or firm names in this publication is for reader information and does not imply endorsement by the authors or their respective institutions of any product or service.

Pesticide Precautionary Statement

This paper may include research involving pesticides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All use of pesticides must be registered by appropriate agencies before they can be recommended.

CAUTION!

Pesticides can be injurious to humans, domestic animals, desirable plants, and fish or wildlife if they are not handled or applied properly. Use all herbicides selectively and carefully. Follow recommended practices for the disposal of surplus pesticides and their containers.

References

- Barnett JP (2014) Direct seeding southern pines: history and status of a technique developed for restoring cutover forests. USDA Forest Service, Southern Research Station General Technical Report SRS-187, Asheville, NC, USA.
- Castro J, Pérez-García M, Lovenstein H, Pedrini S (2026) Seeding pines in the Mediterranean region. *Reforesta* 21: 10-31. <https://dx.doi.org/10.21750/REFOR.21.02.132>
- Deal RL (2018) The Dictionary of Forestry. Society of American Foresters, Bethesda, MD, USA.
- Downer R, Manteuffel-Ross T, Tymon L, Aghai M (2024) Direct seeding for conifer regeneration in the Pacific Northwest: a past, present, and future of operational practices. *J For* 122:171–184. <https://doi.org/10.1093/jofore/fvad050>
- Engel VL, de Souza DC, Parrotta J (2026) An overview of seeding methods to restore tropical forests of Brazil. *Reforesta* 21:105-145. <https://dx.doi.org/10.21750/REFOR.21.07.137>
- Gardiner E, Stanturf J (2026) Seeding bottomland oaks (*Quercus* spp.) in the southern United States. *Reforesta* 21: 166-189. <https://dx.doi.org/10.21750/REFOR.21.09.139>
- Grossnickle SC, Ivetić V (2017) Direct seeding in reforestation – a field performance review. *Reforesta* 4:94–142. <https://doi.org/10.21750/REFOR.4.07.46>
- Harmer R, Kerr G (1995) Creating woodlands: to plant trees or not? In: Ferris-Kaan R (Ed.) *The Ecology of Woodland Creation*. John Wiley and Sons, Chichester, England.
- Huth F, Wehnert A, Tiebel K, Wagner S (2017) Direct seeding of silver fir (*Abies alba* Mill.) to convert Norway spruce (*Picea abies* L.) forests in Europe: A review. *For Ecol Manag* 403:61–78. <https://doi.org/10.1016/j.foreco.2017.08.017>
- Ivetić V, Marinković M (2026) Seeding to establish Ravni Srem oak forests, Northern Serbia. *Reforesta* 21:199-207. <https://dx.doi.org/10.21750/REFOR.21.11.141>
- Lázaro-González A, Andivia E, Hampe A, Hasegawa S, Marzano R, Santos AMC, Castro J, Leverkus AB (2023) Revegetation through seeding or planting: a worldwide systematic map. *J Environ Manag* 337:117713. <https://doi.org/10.1016/j.jenvman.2023.117713>
- Löf M, Miles B, Moe KT, Pohl N, Schönbeck L (2026) Seeding of oak in southern Sweden. *Reforesta* 21: 190-198. <https://dx.doi.org/10.21750/REFOR.21.10.140>

- Löf M, Castro J, Engman M, Leverkus AB, Madsen P, Reque JA, Villalobos A, Gardiner ES (2019) Direct seeding to restore oak (*Quercus* spp.) forests and woodlands. For Ecol Manag 448:474–489. <https://doi.org/10.1016/j.foreco.2019.06.032>
- López-Barrera F, García-Hernández MÁ (2026) Seeding acorns from montane cloud forest restoration in central Veracruz, Mexico: practical experiences. Reforesta 21:146-165. <https://dx.doi.org/10.21750/REFOR.21.08.138>
- Lord J, Moss-Mason K (2026) Seeding for native afforestation in temperate New Zealand forests. Reforesta 21:68-86. <https://dx.doi.org/10.21750/REFOR.21.05.135>
- Pansing E, Tomback D (2026) Seeding of whitebark pine (*Pinus albicaulis*) in western north American subalpine forests: Development and application. Reforesta 21:32-53. <https://dx.doi.org/10.21750/REFOR.21.03.133>
- Scott JD (1970). Direct seeding in Ontario. For Chron 46:453–457.
- Stanturf JA, Dumroese RK, Elliot S, Ivetić V, Khokthong W, Kleine M, Lang M, Löf M, Madsen P, Prescott C, Young T (2024). Advances in forest restoration management and technology. In: Katila P, Pierce Colfer CJ, de Jong W, Galloway G, Pacheco P, Winkel G (eds.) Restoring Forests and Trees for Sustainable Development: Policies, Practices, Impacts, and Ways Forward. Oxford Academic, New York, NY, USA, pp 297–334. <https://doi.org/10.1093/9780197683958.003.0011>
- Stanturf J, Gardiner E (2026) Seeding forest trees. Reforesta 21:208-224. <https://dx.doi.org/10.21750/REFOR.21.12.142>
- Stanturf J, Mansourian S, Kleine M, eds. (2017) Implementing Forest Landscape Restoration, A Practitioner’s Guide. International Union of Forest Research Organizations, Special Programme for Development of Capacities (IUFRO-SPDC), Vienna, Austria.
- Sudrajat D, Yulianti, Rustam E (2026) Seeding of tropical tree species in Indonesia. Reforesta 21:87-104. <https://dx.doi.org/10.21750/REFOR.21.06.136>
- Wang FC, Liu Q, Wang GG (2026) *Pinus massoniana* seeding practices for forest restoration in China. Reforesta 21:54-68. <https://dx.doi.org/10.21750/REFOR.21.04.134>
- Toumey JW (1916) Seeding and Planting: A Manual for the Guidance of Forestry Students, Foresters, Nurserymen, Forest Owners, and Farmers. John Wiley & Sons, Inc., New York, NY, USA.